THE UNIVERSITY OF ALBERTA

PROXIMAL CHANNEL DEPOSITS OF THE HADRYNIAN HECTOR FORMATION, LAKE LOUISE, ALBERTA

by

© ROBERT WILLIAM CHARLES ARNOTT

A THESIS

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DEDICATION

This thesis is dedicated to the love of my sister

Mrs. Wendy (Arnott) Lockhart and to the loving memory

of my mother Mrs. Barbara Ann Arnott.

When the words are in mobile
until you sit down
When you feel they're worth keeping
they're not easily found

Peter Townsend (The Who)(1978)

ABSTRACT

The Hector Formation of Hadrynian age near the town of Lake Louise, Alberta, is comprised of quartz-pebble conglomerates and coarse sandstones, in association with grey-black slate horizons with thin turbidite interbeds. These coarse clastic beds are usually normally graded and structureless. Other less common facies include: slightly disrupted-bedded pebbly sandstones and slate, chaotic conglomerate and slate mixtures, and chaotic dispersed conglomerate and pebbly sandstone. These are possible slide, slump and debris flow deposits.

Outcrops on the west and south faces of Redoubt Mountain expose a well defined, deeply channellized complex filled with thickly-bedded coarse clastic sediments bounded on all four sides by the grey-black slate / thin turbidite horizons. The channel-fill which is at least 135 metres thick, exhibits a multi-storey fining- / thinning-upward cycle, and is interpreted as an ancient submarine canyon-fill.

Facies at the Bath Creek Quarry are very similar to those of Redoubt Mountain but differ by: 1) a decrease in grain size and bed thickness, 2) a greater abundance of slump, debris flow and ungraded trough cross-bedded sandstone facies. This suggests a shallower more proximal slope setting interpreted as a possible near shelf-break margin Tributary Canyon Fill, likely associated with the Main Canyon Fill reported at Redoubt Mountain.

Paleocurrent trends depict a northeastward trending submarine canyon at Redoubt Mountain and a southeastward trending canyon at the Bath Creek Quarry. These directions suggest that the coarse-grained, channellized strata of the Hector Formation were deposited on a generally north / northeastward dipping submarine slope. Petrographic similarity with lithologies of the Canadian Shield beneath the Interior Plains, may suggest that this slope is associated with either a portion of the cratonic continental slope or that of an intracratonic basin.

ACKNOWLEDGEMENTS

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I would like to thank the many people who have helped with various aspects of this thesis. In particular I wish to thank Dr. H.A.K. Charlesworth, Dr. R.A. Burwash, Mr. Q. Goodbody and Mr. P. Beasley for their patience and help with many technical aspects of this thesis. Special thanks is extended to Mr. Bruce 'Shaggy' Hart for his very competent assistance during the summer field work.

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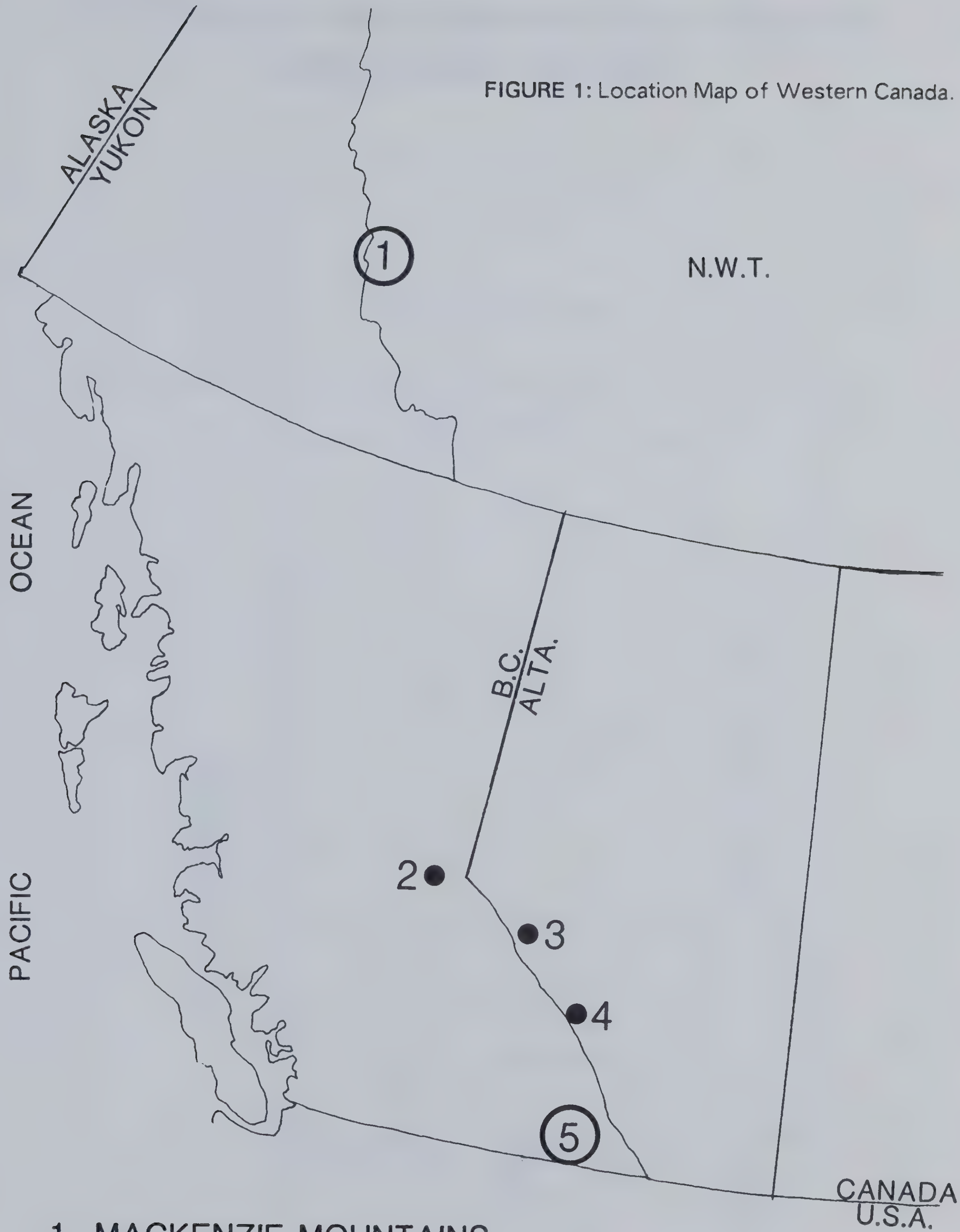
I. INTRODUCTION

The Main Ranges of the Canadian Cordillera near the town of Lake Louise, Alberta (51° 25.5′, 116° 11′) (Figure 1), provide excellent exposure of uppermost Precambrian (Hadrynian) and Lower to Middle Cambrian sedimentary rocks. These rocks are part of a narrow sinuous belt outcropping for 4000 km along the North American Cordillera (Stewart, 1972). Within the Lake Louise / Bow Valley area, uppermost Hadrynian aged rocks belonging to the Miette Group consist of non-fossiliferous conglomerate, sandstone and slate. Walcott (1910), while working at Fort Mountain (now called Redoubt Mountain), stratigraphically sub-divided the Miette Group in this area into the Corral Creek and Hector Formations. These two formations are lithologically similar, but can be stratigraphically differentiated in the field by the appearance of a thin unit of edgewise limestone breccia (used to identify the top of the Corral Creek Formation) and / or, a purple / green slate horizon at the base of the Hector Formation (Figure 2).

Aitken (1969) reported that in the Lake Louise / Bow Valley area, Hector conglomerate and sandstone form thick lens-shaped units within the Hector slates. These thickly-bedded, channel-filling conglomerates and sandstones are normally graded and structureless with erosive basal contacts. Units of this type resemble coarse-grained sediments deposited within channellized deep-marine environments (Walker, 1966). Thin discontinuous interbeds of incomplete Bouma turbidites coupled with the abundance of mass movement and sediment-gravity flow deposits, may indicate a possible submarine canyon origin for these deposits.

This study centred on the Hector Formation at two localties near the townsite of Lake Louise, Alberta: (1) Bath Creek Quarry (51° 27.5′, 116° 06′), situated one kilometre east of the Alberta / British Columbia border, and (2) the west and south faces of Redoubt Mountain (51° 27′, 116° 06′), located six kilometres northeast of the Lake Louise townsite (Figure 3).

FIGURE 1: Location Map of Western Canada.



1 MACKENZIE MOUNTAINS

2 CUSHING CREEK

3 JASPER

4 LAKE LOUISE

5 PURCELL MOUNTAINS

UPPERMOST PRECAMBRIAN STRATIGRAPHY
LAKE LOUISE, ALBERTA

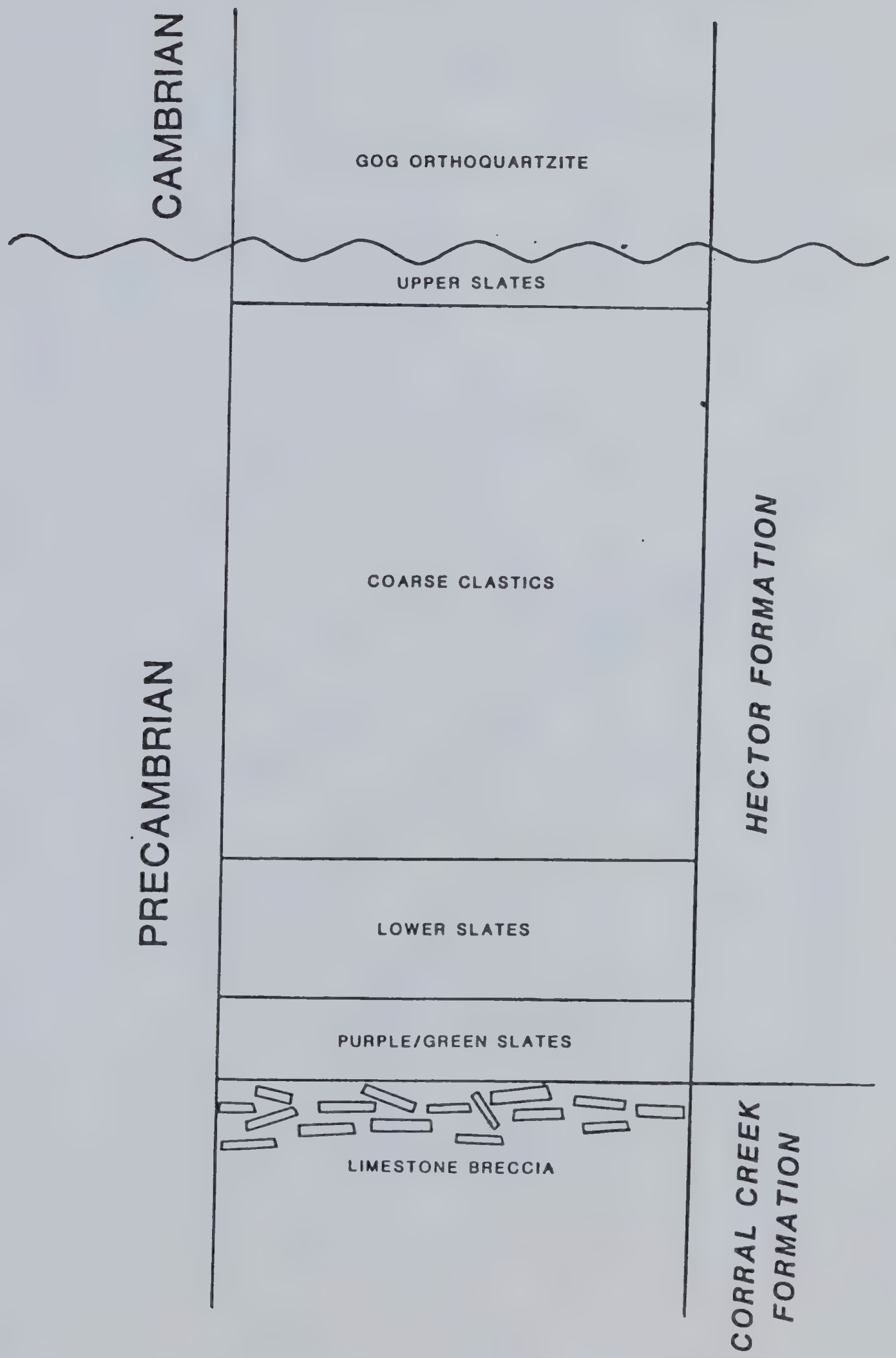


FIGURE 2: Upper Precambrian Stratigraphy, Lake Louise, Alberta.

STUDY LOCATION MAP LAKE LOUISE, ALBERTA

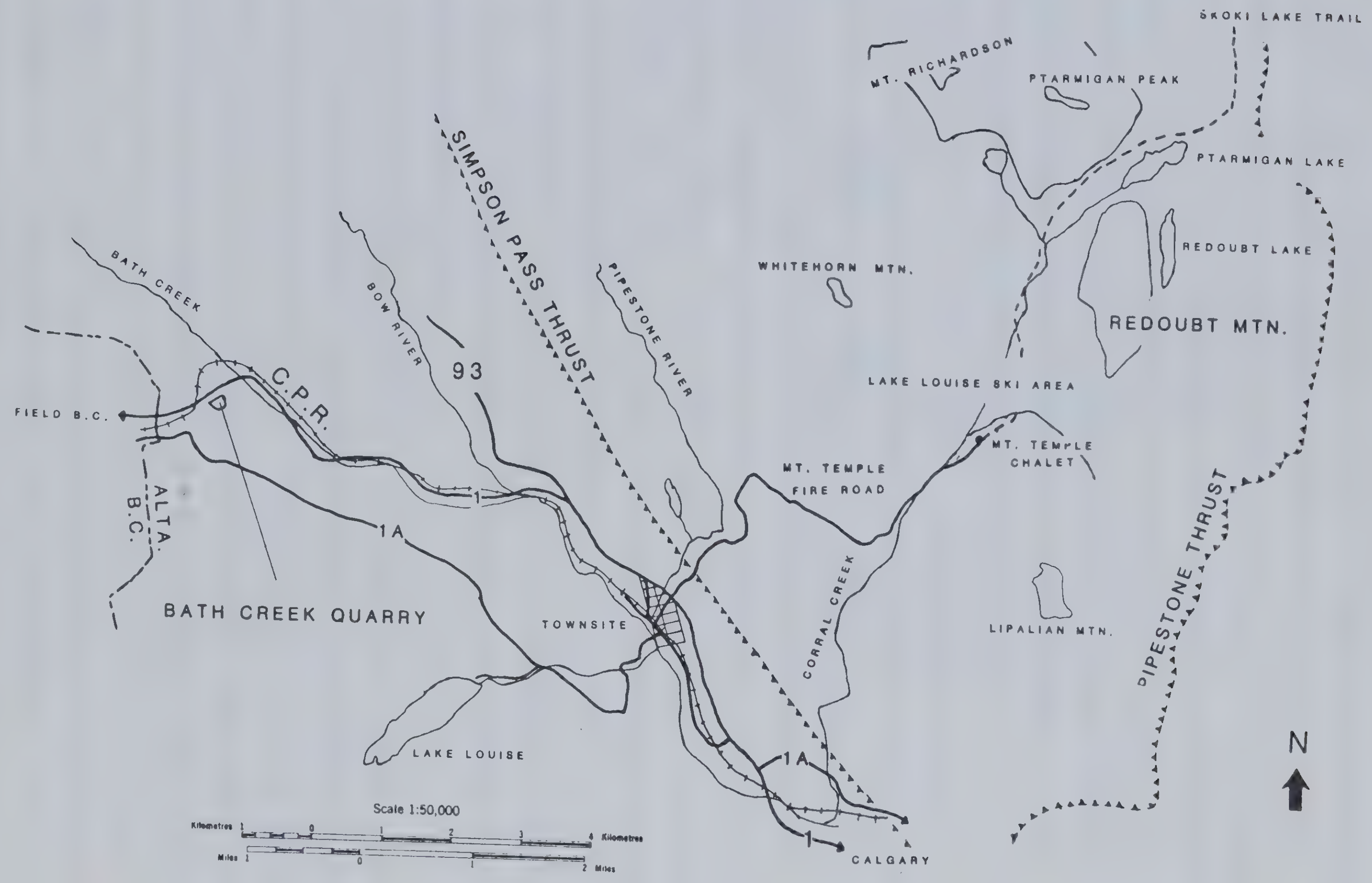


FIGURE 3: Study Location Map Lake Louise, Alberta.

A. REGIONAL STRATIGRAPHY OF THE WINDERMERE SUPERGROUP

The Rocky Mountain Fold and Thrust Belt of the Canadian Cordillera consists partly of miogeoclinal strata deposited over a period of 1000 million years along the west coast of the North American craton. The initial deposits of the Cordilleran miogeocline unconformably overlie (Douglas, *et al.*, 1970, 1976; Stewart, 1972) and transgressively onlap (Price and Mountjoy, 1972) Archean and Early Aphebian crystalline basement rocks (Douglas, *et al.*, 1970, 1976). Basement rocks show a well developed northeast tectonic trend and are believed to represent a western extension of the Bear and Churchill Provinces of the Canadian Shield (Burwash, *et al.*, 1962, 1964)(Figure 4). Upper Proterozoic sedimentary successions of the Cordilleran miogeocline, within the Southern Canadian Cordillera, are known as the Purcell and Windermere Supergroups.

The older, mainly Helikian Purcell Supergroup is restricted to outcrop in the Southern Rocky Mountains and adjacent Purcell Mountains, and to the north within the Mackenzie Mountains and Northern Rocky Mountains (Figure 1)(Gabrielse, 1972). Sedimentation was initiated by uplift and erosion of the crystalline basement during the Hudsonian Orogeny (Burwash, *et al.*, 1964). Deposition of well-sorted, fine-grained shallow marine clastic and carbonate strata took place within a northwest-to-southeast trending miogeoclinal trough (Stewart, 1972; Monger, *et al.*, 1972). Up to twenty kilometres of sediment are proposed to comprise the Purcell Supergroup (McMeechan and Price, 1982). This indicates a long-standing condition of relatively equal sedimentation and subsidence (Gabrielse, 1972).

Purcell sedimentation was terminated by the Late Precambrian East Kootenay Orogeny (White, 1959). Using K / Ar dating, (Burwash, *et al.*, 1964) dated this orogeny at 750-850 Ma. However, later work by Ryan and Blenkinsop (1971), using Rb / Sr dating, revised this date to approximately 1330-1350 Ma. Deformation associated with the East Kootenay Orogeny included regional uplift, block faulting, folding, metamorphism and granitic intrusion, interpreted by some workers to represent a single tectonic event separating Purcell and Windermere sedimentation periods (White, 1959; Burwash, *et al.*, 1964; Douglas, *et al.*, 1970, 1976; Monger, *et al.*, 1972; Gabrielse, 1972). More recent work by McMeechan and Price (1982), proposes a multi-phase orogenic history separating Purcell and Windermere sedimentation (Figure 5). In their model, these authors suggest the

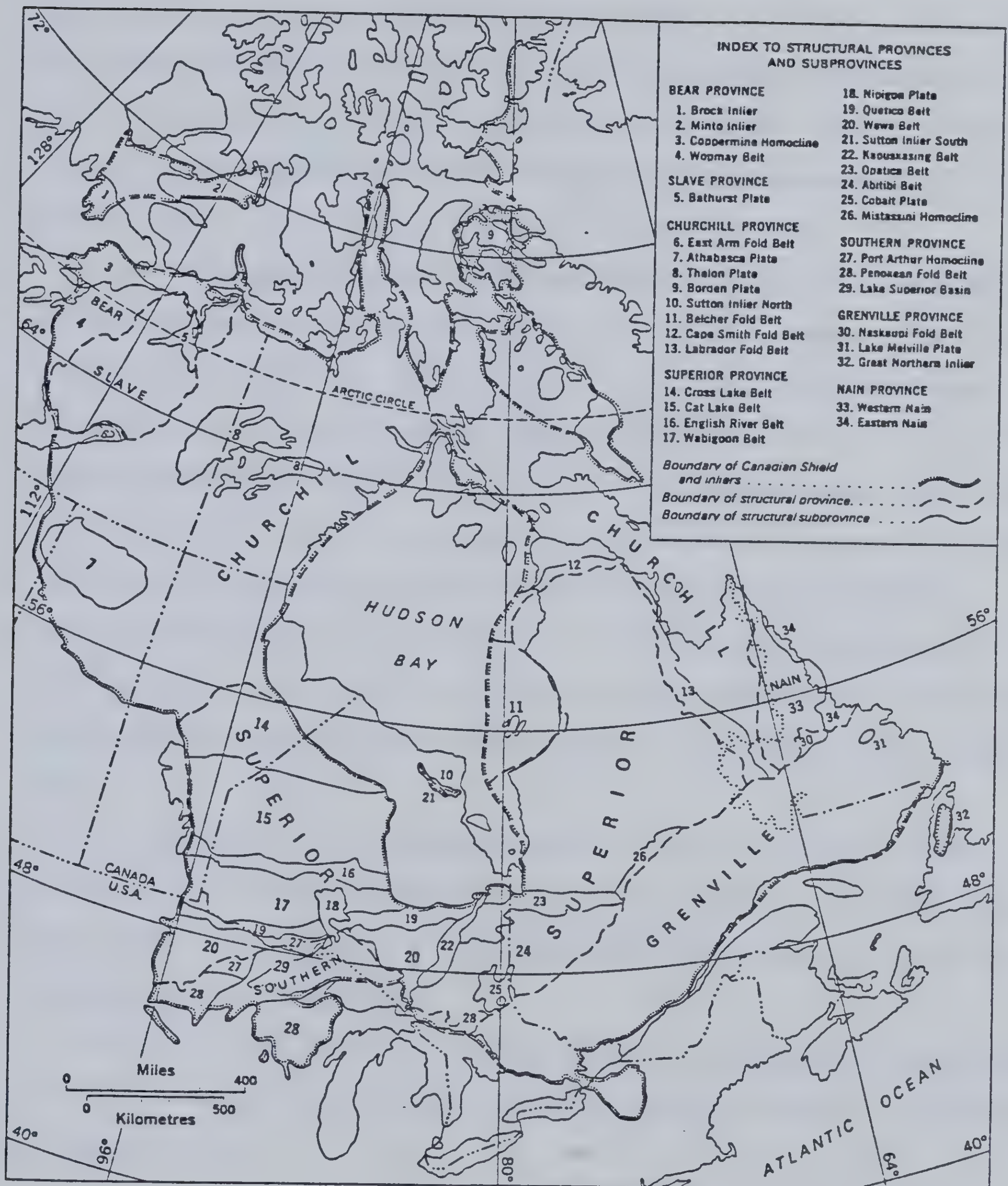


FIGURE 4: Precambrian Basement Map of Canada (Douglas, *et al.*, 1970, 1976).

existence of two distinct orogenic events. The first, which they call the East Kootenay Orogeny, dates at 1300-1350 Ma and coincides with the termination of Purcell sedimentation. Deformation included the development of folds and a cleavage at lower stratigraphic levels. The second orogeny, called the Goat River Orogeny, is dated at approximately 750-850 Ma. This later event occurred during the early stages of Windermere sedimentation and involved uplift and block faulting. However, it should be noted that this latter date is an arithmatic average of K/Ar dates obtained from various studies at numerous localities within the Canadian Rocky Mountains.

The Windermere Supergroup, representing the last 200 Ma. of Precambrian time, is extensively exposed along a narrow sinuous belt extending the length of the Canadian Cordillera (Figure 6)(Gabrielse, 1972; Monger, *et al.*, 1972). In the Southern Rocky Mountains the Windermere Supergroup, reported to be up to 6 km. thick (Young, 1979), lies unconformably above the Purcell Supergroup and is unconformably overlain by the Lower Cambrian Gog Group orthoquartzite and its equivalents. To the north, in the Jasper area, the upper contact between the Windermere and the Gog Group is locally conformable (Charlesworth, *et al.*, 1967). The Windermere represents a westward thickening- and westward-fining wedge of poorly-sorted conglomerate and finer-grained clastic sedimentary rocks deposited within a north-to-south trending trough (Young, *et al.*, 1973).

Source terrains for Windermere sediments were the underlying crystalline basement rocks of the Canadian Shield to the east (Mountjoy and Aitken, 1963; Aitken, 1969; Stewart, 1972; Young, *et al.*, 1973) and uplifted Purcell rocks both to the east and west (Douglas, *et al.*, 1970, 1976).

Based upon regional work, the Windermere Supergroup has been sub-divided into the following, stratigraphically ascending, lithologic divisions (Young, *et al.*, 1973; Poulton and Simony, 1980):

GRIT DIVISION

This lower division consists of immature sandstones, composed of quartz, minor amounts of plagioclase (mostly albite) and potash feldspar, chert and sedimentary rock fragments. Beds are characteristically coarse-grained, poorly-sorted, normally graded and

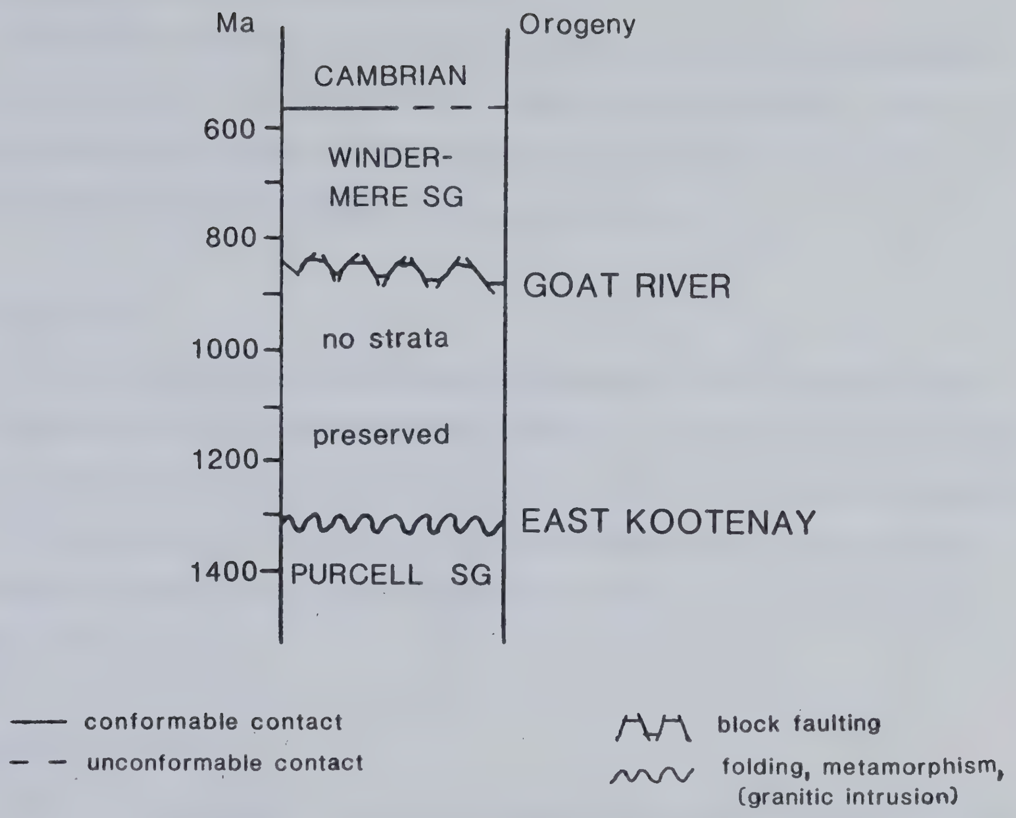


FIGURE 5: Orogenies of the Upper Precambrian (From McMeechan and Price, 1982).

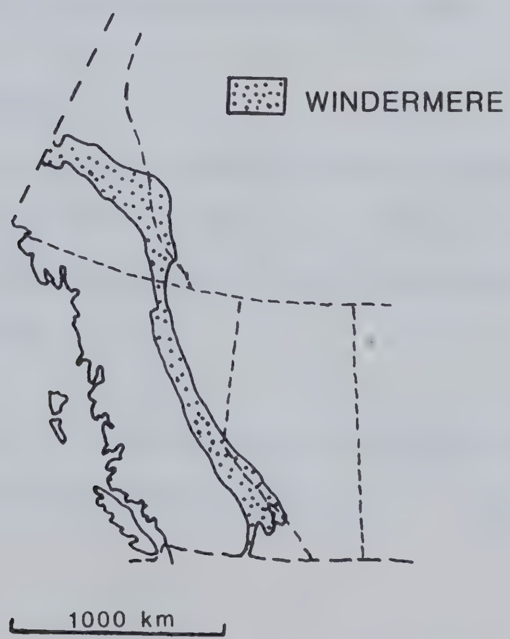


FIGURE 6: Outcrops of the Canadian Windermere Supergroup (From Monger, *et. al.*, 1972).

structureless. Basal scours, channels and slate rip-up clasts are common and point to the erosive nature of the depositional possesses.

Deposition of the coarse-grained beds was from episodic high-concentration sediment-gravity flows (Poulton and Simony, 1980). Thin shale interbeds, providing the source for slate rip-up clasts, represent deposition from both normal on-going hemipelagic fall-out and low velocity dilute nepheloid flows.

SLATE DIVISION

This division is characterised by grey-black slates with thin interbeds of either Bouma sequence CD siltstone or sandstones turbidites. Lithologies become increasingly calcareous and arenaceous upsection. This suggests a gradual shoaling of the depositional basin. Deposits of the Slate Division are mainly hemipelagic muds. These fine-grained sediments accumulated within a deep marine trough, which occasionally had an influx of "distal" turbidites.

CARBONATE DIVISION

Massive dolomites are the primary lithology, with only minor amounts of clastic sediment. Exposures of this division are discontinuous and shows great thickness variation. Lithologies suggest carbonate and off-bank deposition analogous to the modern shallow water Bahamian model (Poulton and Simony, 1980).

UPPER CLASTIC DIVISION

This division is only locally preserved beneath the regional sub-Paleozoic unconformity. Shale, well-sorted sandstone and carbonate are the primary lithologies. Sandstones show parallel laminations and cross-stratification, graded bedding and a great diversity of trace fossils.

Christie-Black, *et al.* (1980) proposed the following history of Windermere sedimentation, and is similar to the lithologic model of Young, *et al.* (1973) and Poulton and Simony (1980):

(1) Event 1 is characterised by intense tectonic activity. Crustal extension responsible for widespread rifting is post-dated by continental break-up and subsequent separation. A wide array of sediment-gravity flows are deposited within subsiding, fault-bounded basins.

Sedimentary deposits of event (1) correlate with those characterising the Grit Division, (Young, *et al.*, 1973; Poulton and Simony, 1980).

(2) Event (2) is represented by regional glaciation, with sediments deposited within marine basins marginal to a large ice sheet. Event (2) is equivalent to the Grit Division (Young, *et al.*, 1973; Poulton and Simony, 1980).

(3) Event 3 consists of a glacial recession accompanied by a eustatic rise in sea level. This rise in sea level effectively removed the depositional basin from direct coarse clastic input, resulting in shale accumulation within this deep marine environment. Event (3) is correlative with the Slate Division (Young, *et al.*, 1973; Poulton and Simony, 1980).

(4) Event (4) is marked by the progradation of shallow water carbonates and clastic sediments, representing a possible marine regression within a largely fault-controlled basin. Tectonic domination of the basin produces a complex palaeogeography, resulting in heterogeneous lateral facies relationships. Event 4 would appear to be correlative with the lithologies and outcrop pattern indicative of the Carbonate Division (Young, *et al.*, 1973; Poulton and Simony, 1980).

(5) Event 5 corresponds to a cessation of growth fault activity and a return of tectonic stability. A eustatic sea level rise lead to renewed deposition of fine clastic sediments. This event corresponds to the lithologies of the Upper Clastic Division (Young, *et al.*, 1973; Poulton and Simony, 1980).

B. LOCAL SETTING OF THE MIETTE GROUP

STRUCTURAL GEOLOGY

During Helikian to Late Jurassic time, sedimentation within the Cordilleran Geocline was dominated by the development of a carbonate, shale and sandstone continental terrace wedge. This wedge attained a maximum thickness of 12 km. to 14 km. Overlying these sediments is approximately 6 km. of a clastic wedge, contemporaneous with the Late Jurassic to Early Tertiary Cordilleran mountain building event associated with the Laramide phase of the Columbian Orogeny (Wheeler, *et al.*, 1972)

The Rocky Mountain Fold and Thrust Belt of the Canadian Cordillera is characterised by two distinct structural levels: 1) the passive infrastructure of the underlying unbroken crystalline basement rocks and 2) the anisotropic sedimentary suprastructure which has undergone northwestward shortening (Price and Mountjoy, 1970). Shortening of the sedimentary cover has occurred along an array of low-angle and discontinuous (interleaved) shear surfaces which all merge into a basal decollement zone above the crystalline basement.

Distinct lithologic, structural and topographic domains have enabled the sub-division of the entire Fold and Thrust Belt into the following four sub-parallel provinces, from east to west they are: 1) Foothills 2) Front Ranges 3) Main Ranges 4) Western Ranges (North and Henderson, 1954)(Figure 7).

The study areas at the Bath Creek Quarry and Redoubt Mountain lie within the eastern sector of the Main Ranges structural province. Structural style in this area is controlled by a thick competent unit of Lower Cambrian orthoquartzites belonging to the Gog Group and its equivalents (Balkwill, 1972). Upper Precambrian and Lower to Middle Cambrian strata have been folded into broad open folds. These folds plunge toward the north (North and Henderson, 1954) and are cut by a series of cross-cutting *en-echelon* normal gravity faults (Price and Mountjoy, 1970; Cook, 1975). Southwest dipping thrust planes underlie the entire study area. The Simpson Pass Thrust underlies the Bath Creek Quarry area; the Pipestone Thrust underlies the Redoubt Mountain area. Palinspastic reconstruction, using structural maps compiled by Price and Mountjoy (1970), shows a 20 km. W-E structural shortening along the Simpson Pass Thrust and 16 km. W-E shortening

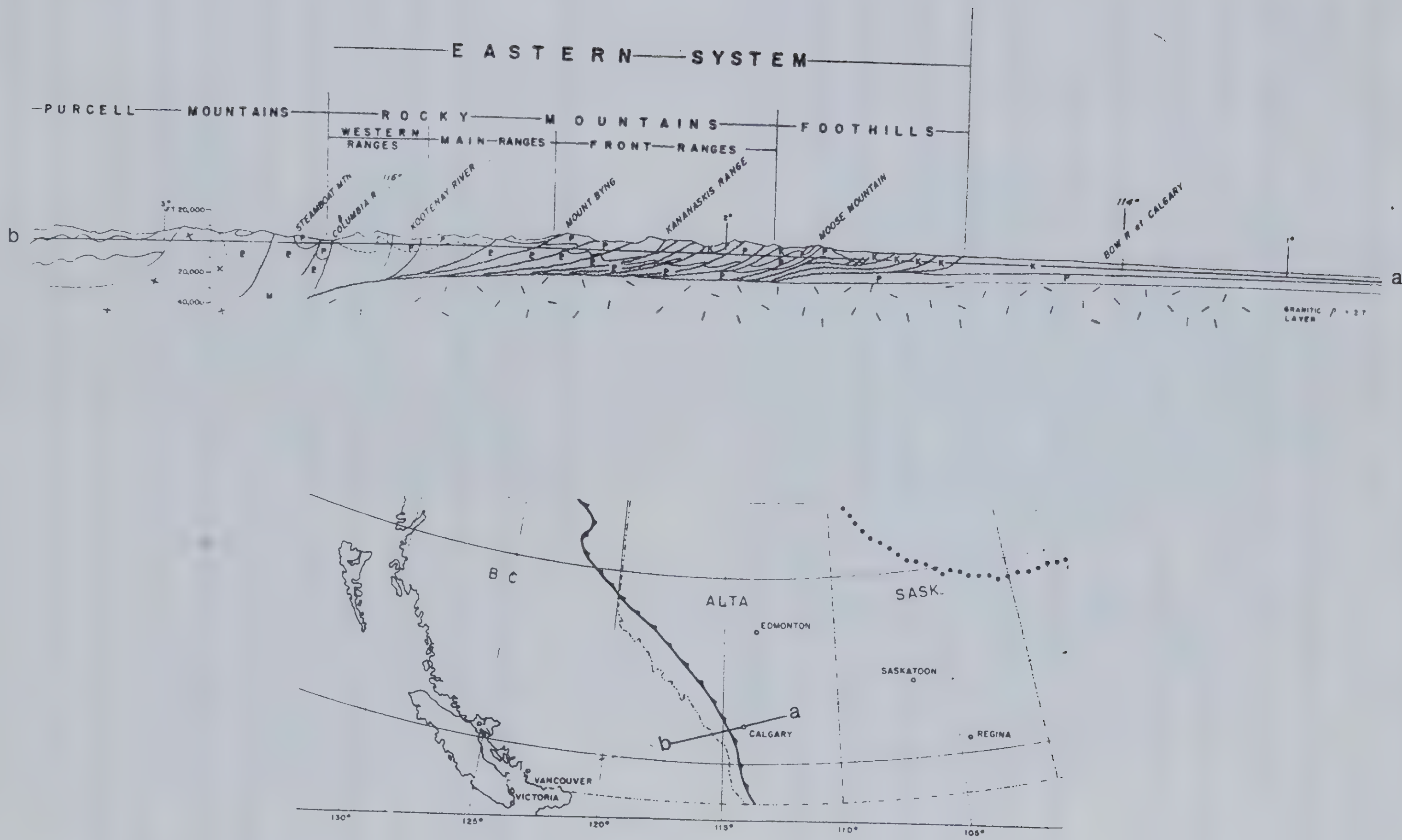


FIGURE 7: Structural Provinces of the Southern Canadian Cordillera (From Nelson, *et al.*, 1964).

along the Pipestone Thrust.

Bath Creek Quarry lies on the eastern limb of the Sherbrooke Lake Syncline and shows an average bedding orientation of $160^0/20^0$ SW. Hector Formation outcrops are exposed in a series of small stacked ridges typically bounded by fault contacts (where visible). Small-scale normal faults, with displacements that a less than 0.5 metres, are common and pose no real problem in bed correlations. A fault of unknown size and displacement delimits the western upper part of Section 12 (Figure 8). Extensive quartz mineralization and slickenstriae occur on this fault plane.

Structure in the Redoubt Mountain area has been poorly documented. The main structural feature on Redoubt Mountain is a very gently folded syncline (easily identified in the bedded Gog orthoquartzites). Bedding orientations vary only slightly throughout the measured sections and average approximately $130^0/37^0$ NE. Sub-parallel to bedding tectonic fracture surfaces are very common and may be a result of close proximity to the Pipestone Thrust. These surfaces are commonly observed in medium and coarse-grained sandstones, particularly in the upper portions of normally graded beds.

LOCAL STRATIGRAPHY AND STUDY LOCATIONS

The oldest rocks exposed in the Lake Louise / Bow Valley area of Alberta are those of the Upper Proterozoic (Hadrynian) Miette Group. In the Cushing Creek area of British Columbia, the Miette Group is reported to attain a minimum thickness of 5050 metres (Carey and Simony, 1984). Walcott (1910) was the first to recognize and study these Precambrian rocks but erroneously equated them to Beltian (equivalent to the Purcell Supergroup in Canada) rocks of the northwestern United States. During this early work near Fort Mountain (now called Redoubt Mountain), Walcott recognized and described two non-fossiliferous formations, the sandstone-rich Corral Creek Formation and the overlying slatey Hector Formation. Walcott reported that the Hector Formation in this area is unconformably overlain by the Lower Cambrian. However, later work by Aitken (1969), showed that Walcott erred in placing the Lower Cambrian contact at the base of a series of conglomerate lenses cut into the Hector Slates. Aitken's revised stratigraphic model of

FIGURE 8: Fault Plane West of Section 12 Bath Creek Quarry (fault plane is coated with quartz mineralization and slickenstriae).

the Upper Precambrian in the Lake Louise area, places the Lower Cambrian contact at the base of the fossiliferous Gog Group orthoquartzites. In this model, Aitken includes all strata between and including Walcott's Hector Slates (equivalent to Aitken's purple / green and lower slate units) and the Lower Cambrian Gog Group, to be that comprising the Upper Precambrian Hector Formation (Figure 2). Under present useage, the Corral Creek Formation and Hector Formation comprise the Miette Group of uppermost Windermere in the Lake Louise / Bow Valley area.

In this study, two locations near the town of Lake Louise, Alberta were selected for analysis. Bath Creek Quarry (51° 27.5', 116° 06') is located approximately 1 km. east of the Alberta / British Columbia border along the Trans-Canada Highway. This area, described by Hein (1982b), was selected for further analysis because of its accessibility and the appearance of the purple / green slate horizon. The Hector Formation is exposed in a series of small ridges on both the north and south sides of the highway (Figure 9). Ridges were selected for measurement if they exceeded 2-3 metres, or if their location in the field aided in lateral or vertical bed correlations.

Redoubt Mountain (51° 27', 116° 06') is located approximately 6 km. northeast of the Lake Louise townsite, and is the location of the type sections of the Corral Creek and Hector Formations (Walcott, 1910). Selection of this area was based on its accessibility, easy recognition of both marker horizons and availabiltiy of structurally undeformed outcrop. Seven complete vertical sections showing almost uninterrupted exposure from the basal grey-black slates to the Lower Cambrian Gog Group were selected for measurement (Figure 10). These sections were also selected in order to facilitate correlations.

The Hector and underlying Corral Creek Formations are lithologically similar. Differentiation of the two formations in the field depends upon the occurrence of specific marker units - namely the edgewise limestone breccia beds (Figure 11), and the purple / green slate hoizons. Earlier studies have suggested the use of the edgewise limestone breccia bed (5-8 metres thick at Redoubt Mountain) to define the top of the Corral Creek Formation (Aitken, 1969). Unfortunately, this bed can be both locally and regionally discontinuous. Another more extensive and easily recognized marker horizon consists of purple slates with minor intercalations of green slate. This purple / green

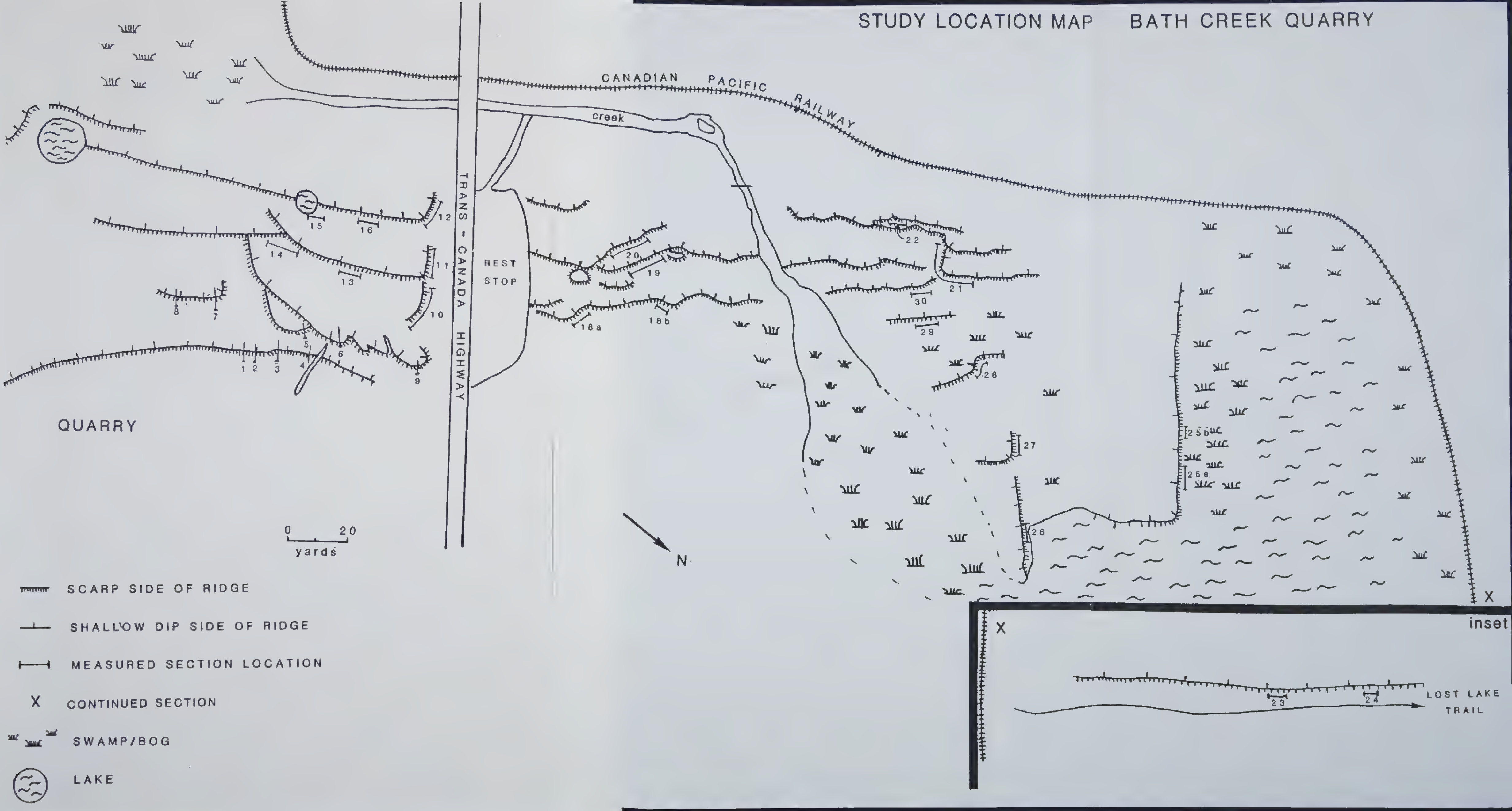

STUDY LOCATION MAP BATH CREEK QUARRY
CANADIAN PACIFIC RAILWAY
creek
TRANS - CANADA HIGHWAY
REST STOP
QUARRY
0 20
yards
N
X
inset
LOST LAKE TRAIL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 18a 18b 19 20 21 22 23 24 25a 25b 26 27 28 29 30
SCARP SIDE OF RIDGE
SHALLOW DIP SIDE OF RIDGE
MEASURED SECTION LOCATION
X CONTINUED SECTION
SWAMP/BOG
LAKE

FIGURE 9.

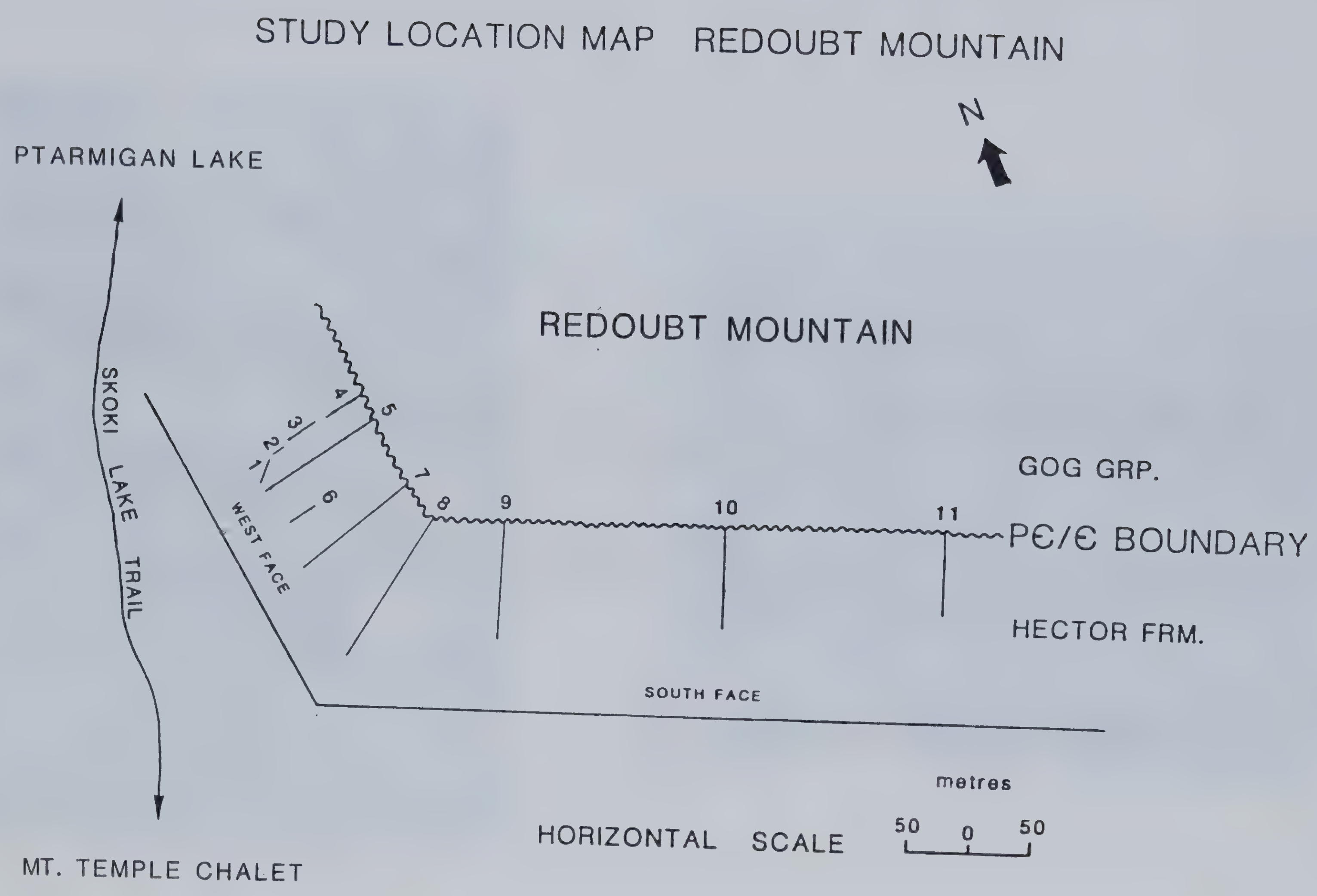


FIGURE 10: Study Location Map - Redoubt Mountain.

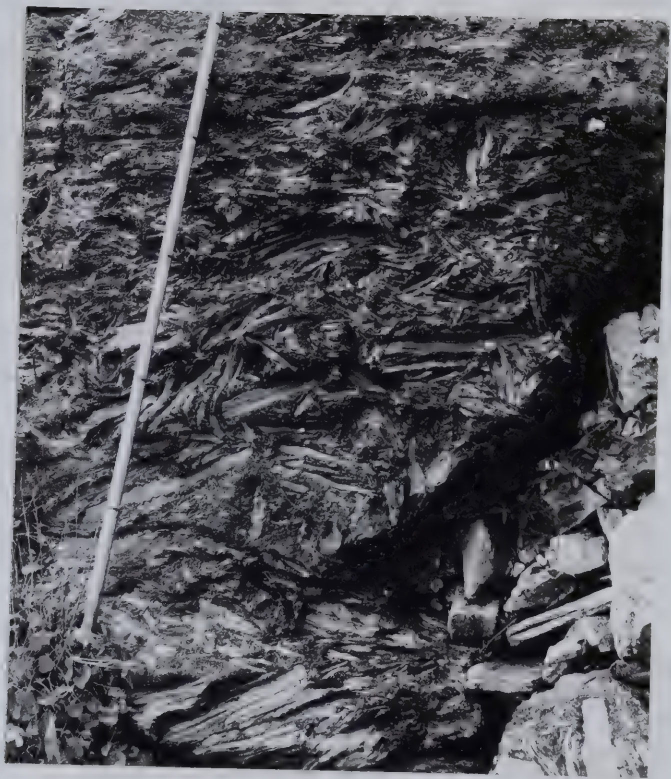


FIGURE 11: Limestone Breccia (staff is 1.5 metres long).

FIGURE 12: Lower Slate / Coarse Clastic Contact.

coloured slate horizon is approximatety 15 metres thick on the southwest corner of Redoubt Mountain and 20-25 metres thick at Bath Creek Quarry. Directly overlying these slates is a thick monotonous sequence of grey-black slate with abundant thin interbeds of fine-grained upper division Bouma turdidites (BCD,CD). This dark slaty horizon, called the Lower Slates by Aitken (1969), is abruptly overlain by very coarse quartz-pebble conglomerate and coarse-grained immature sandstone (Figure 12). At Redoubt Mountain, coarse-grained sediments represent the fill of a minimum 135 metre deep channel cut into strata of the lower slates (Figures 13,14 and Appendix VI). Unfortunately, at Bath Creek Quarry the lower slate / coarse clastic contact is only rarely observed, making the interpretation of the paleoenvironment more subjective. The contacts between the coarse clastics and the lower slates are erosive along the sides and base of the channel-fill. These overall relationships suggest that the channel-fill may represent a deep-water submarine canyon deposit.

The coarse clastic channelled sediments are conformably overlain by a grey-black slate horizon with thin interbeds of fine-grained turbidites. This upper slaty unit, the Upper Slates of Aitken (1969), is found at both study locations, but is better exposed at Redoubt Mountain. The upper slaty unit was subdivided as follows: (1) the basal sub-unit, predominately a thin-bedded fine-grained turbidite horizon with minor slate interbeds; and, (2) the upper sub-unit, dominately slate with minor thin turbidite interbeds. The upper contact of the Upper Slate unit with the Lower Cambrian Gog orthoquartzites is covered at Bath Creek Quarry, but is well exposed at Redoubt Mountain (Figure 15). During this study, detailed section measuring up to the Hector / Gog contact (at Redoubt Mountain) gave concrete evidence of a significant amount of relief along this contact (metre-scale). This suggestion of an unconformable contact has also been regionally documented by Aitken (1969). At Bow Peak (28 km NW of Redoubt Mountain), Aitken reports a 3° angular unconformity separating Upper Precambrian (Hector Formation) and Lower Cambrian (Gog Group) strata.

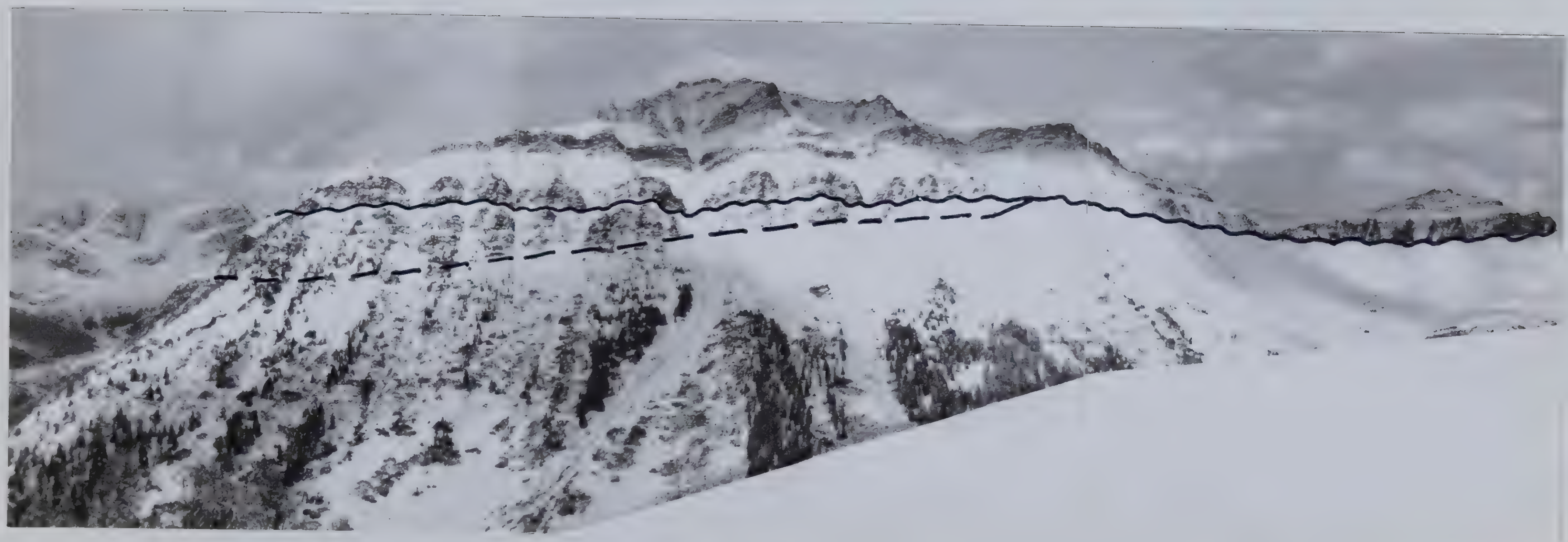


FIGURE 13: South Face of Redoubt Mountain.
Wavy line represents the Precambrain / Cambrian contact (Hector / Gog contact). Dashed line marks out the large-scale channel feature.

FIGURE 14: West Face of Redoubt Mountain.
Wavy line represents the Precambrain / Cambrian contact (Hector / Gog contact). Dashed line marks out the large-scale channel feature.

FIGURE 15: Precambrian Hector Formation / Cambrian Gog Group contact (contact lies slightly above the 25 cm mark (lowermost ring) on the staff).

C. SUBMARINE CANYONS --- THE STATE OF KNOWLEDGE

The Continental Slope is the steepest physiographic province of the continental margin, with average gradients of 3° - 6° (Bouma, 1979). The Slope begins at the Continental Shelf-Break and continues downslope to a point where the gradient becomes less that 0.025° (continental rise province). Undissected continental slopes are a modern global rarity (Shephard and Dill, 1966; Piper and Normark, 1982). The surface physiography of continental slopes is often deeply incised or gullied by submarine canyons. Submarine canyons are concave-up in longitudinal-section view; straight to sinuous in plan view; and steep-walled V-to-U shaped valleys in cross-sectional view. Down-axis gradients are 5° - 10° or greater. Submarine canyons commonly emerge on continental shelves and extend into the deep-sea basin. Observation in modern canyons point to a rapid but intermittent downslope movement of sediment (Shephard and Dill, 1966). Turbidity currents and slumping are the dominant transporting agents, while other sediment-gravity flow processes although active, play a proportionally less important role (Stanley, 1975).

Numerous models have been proposed to explain the origin of submarine canyons. The two most commonly accepted models involve subaerial emergence and erosion or, alternatively, submarine inception. The subaerial origin is due to fluvial downcutting of the exposed continental shelf and / or upper continental slope during periods of low eustatic sea levels (commonly associated with glaciation)(Shephard and Dill, 1966). Under these low stands of sea level, fluvially-derived coarse-grained sediment is discharged directly onto the upper continental slope. The rapid input of coarse sediment to the shelf-break margin augments the generation of sediment-gravity flows, aiding in the further development of steep-walled submarine canyons.

Submarine inception involves erosion into poorly-consolidated shelf sediments offshore from fluvial point sources. Several independant studies (Felix and Gorsline, 1971; Reimnitz and Gutierrez-Estrata, 1970; Herzer and Lewis, 1979) have demonstrated that shifting sediment point sources (commonly associated with fluvial migration) have resulted in the construction of new submarine valleys by sediment-gravity flow erosion.

Continual downslope flushing of sediment by sediment-gravity flows is essential for the continued activity of a submarine canyon. Once deactivated, (*i.e.* no longer a

primary site of erosive large-scale sediment-gravity flows) the canyon will begin to fill. Continued filling leads to the reduction of differential bathymetric relief within the canyon. The result is a decrease and eventual cessation of effective sediment-gravity flows along and into the canyon (Herzer and Lewis, 1979).

Submarine canyon-fills of various geologic age and lithotypes have been documented (Lowe, 1972; Stanley and Unrug, 1972; Stanley, 1975; Cossey and Ehrlich, 1978; Almgren, 1978; Herzer and Lewis, 1979; Lohmar, *et al.*, 1979). Like fluvial and some shelf channels, submarine canyon deposits tend to be coarser than the sediments into which they erode. Coarse-grained canyon-fills are characterised by laterally restricted, thick, massive and often amalgamated sedimentary units with rare turbidite interbeds. Bounding the fill on at least three sides are the thinly-bedded, fine-grained continental or intercanyon slope deposits (Stanley, 1975).

Recent studies have advanced our understanding of coarse-grained, deep-sea depositional processes. However, their detailed sedimentary processes are still poorly understood. This is a consequence of the relatively uncommon occurrence of coarse-grained deep-sea sediments in the geologic record and the inability to adaquately model deposition of these sediments in the laboratory.

The major problem in understanding coarse-grained deep-sea sediments , is the lack of knowledge concerning the remobilization and resedimentation processes. This is because during the history of a sediment-gravity flow, one or more sediment support mechanisms (to be discussed later) may dominate at any one time and / or space. Walker (1978) has proposed a conceptual model depicting the downslope transitions of sediment-gravity flows (Figure 16). This suggests that any one deposit may exhibit features characteristic of more than one type of sediment-gravity flow. Generally however, the characteristics of one type of sediment-gravity flow will dominate. This presents problems for process interpretation when dealing with the sedimentological features of such rocks.

D. PURPOSE OF THE STUDY

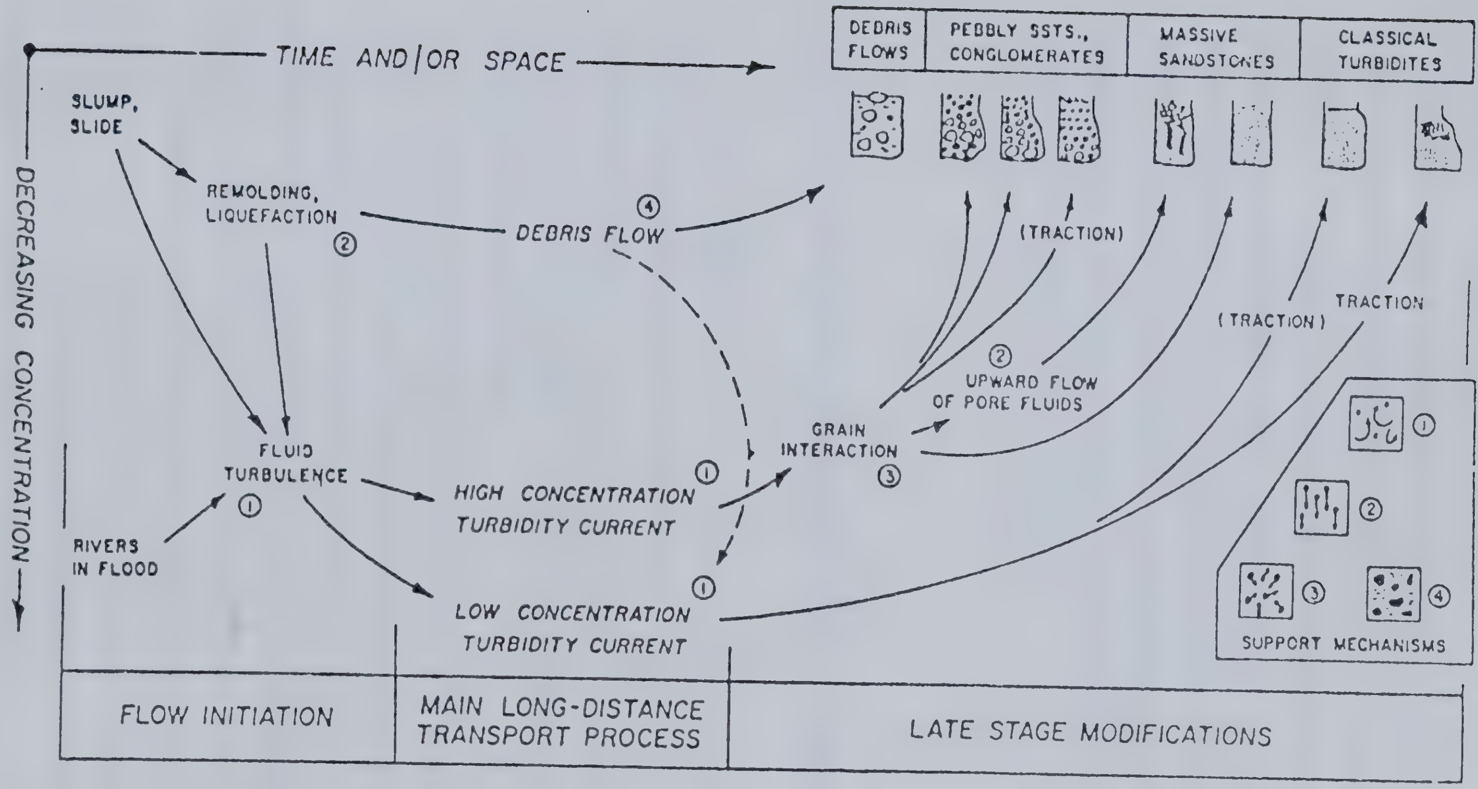
The main objectives of the study were four-fold:

1) To describe in detail the sedimentary structures of each of the measured beds at Bath Creek Quarry and Redoubt Mountain.

2) To interpret the sedimentary processes which deposited the coarse clastic sediments at both study areas.

3) To reconstruct the ancient depositional setting of the coarse clastic units observed at the study areas.

4) To observe the nature of the controversial sub-Paleozoic contact.



—Processes of initiation, long-distance transport, and deposition for currents transporting sediment into deep water. Framework is one of time and/or space, and concentration of flows. Grain-supporting mechanisms (insert, lower right) include: 1, fluid turbulence; 2, liquefaction; 3, collision between individual grains (dispersive pressure in grain flow); and 4, matrix strength (as in debris flow). Modified in discussion with Middleton (personal commun.) from Middleton and Hampton (1976), to show possibility of debris flows becoming turbulent, and to eliminate grain flows as long-distance transport processes.

FIGURE 16: Sediment-Gravity Flow Continuum (From Walker, 1978).

II. CHAPTER 2

A. INTRODUCTION

As mentioned in the latter part of Chapter 1, the coarse channel-filling sediments at Bath Creek and Redoubt Mountain may represent the fills of two ancient submarine canyons. Within modern submarine canyons, remobilization and resedimentation of coarse clastic sediment is accomplished by sediment-gravity flow and mass movement processes. The following section is a brief summary of the characteristic transport and depositional styles of each of the various sediment-gravity flow and mass movement processes. This will then set the basis for process interpretation of each of the sedimentary facies identified in this study.

B. DEEP SEA RESEDIMENTATION PROCESSES AND THEIR DEPOSITS - A REVIEW

Gravity sliding, slumping, and sediment-gravity flows, are the primary mechanisms for the transport and deposition of sediments to the deep-sea. Gravity slides and slumps are simple mass movements characterised by only slight to moderate internal deformation. This contrasts with the extensive deformation and remobilization of sediment that occurs within sediment-gravity flows.

A sediment-gravity flow or mass-gravity flow is defined as sediment transport in which movement parallel to the bed is a result of the force of gravity acting on the sediment within the flow (Middleton and Hampton, 1973, 1976). These flows exhibit non-Newtonian fluid behaviour and will continue in a downslope direction until the internal cohesive yield strength exceeds the external gravitational pull.

Several types of sediment-gravity flow exist, each differentiated by the dominant sediment support mechanism active during movement. These include: 1) buoyancy 2) dispersive pressure 3) cohesive matrix strength and 4) turbulence. Below is a brief discussion of the different types of sediment-gravity flow and their characteristic deposits.

TURBIDITY CURRENTS.

Turbidity currents are density currents which are initiated by some event (often catastrophic in nature) and move downslope away from their source (Middleton and Hampton, 1973, 1976). Sediment carried within turbidity currents is supported against the force of gravity by an upward component of fluid turbulence. Downslope movement will continue as long as there is a continued supply of a sediment-water mixture to replenish that lost during flow. This enables the maintenance of a continual density gradient with the surrounding ambient fluid (sea water). The classic flume experiments of Middleton (1966a, 1966b, 1967) resulted in a tripartite breakdown of a turbidity current. These three morphological units are: 1) head 2) body and 3) tail.

The head is generally thicker than the rest of the current and has a distinct lobate shape and velocity when in a "healthy" state. Turbulence is greatest in this part of the flow where diverging flow inhibits the vertical variation in suspension, concentration and deposition. Fine-grained material may get caught up within turbulent eddies found at the back of the head. These eddies are pulled from the head, with deposition of the fine-grained sediment in a mixed layer (also called an entrained layer) carried along on top of the main flow. Coarse-grained sediment during the course of the flow is concentrated within the head, helping to augment basal scouring.

The body of the current lies immediately behind the head and comprises the greater part of the flow. It is of almost uniform thickness and closely approximates a steady uniform flow (autosuspension). Its main function is to act as a source of the sediment-water mixture constantly being supplied to the head. This maintains the density gradient between the flow and the ambient fluid, thereby sustaining movement. Directly above the the body is the mixed or entrained layer. Sediment derived by mixing of the ambient fluid with the upper region of the body, plus sediment brought in by turbulent eddies from the head, form a low concentated sediment-water layer entrained by the current below. This layer may, because of its inertia and low flow resistance, continue to flow even after the body and the tail have passed by. This may result in the reworking of the upper units of sediments deposited by the main current.

The tail is a region where the flow thins rapidly and becomes more dilute. Velocities are much reduced compared to the rest of the flow resulting in rapid deposition

of its fine-grain sediment load.

Bouma (1962) recognized a recurring, systematic deposit within flysch sediments. He noted that these deposits which Kuenen (1957) had called "turbidites", were characterised by five distinct intervals. From top to bottom these intervals are:

(a) Pelitic interval

(b) Upper interval of parallel lamination

(c) Interval of current ripple lamination

(d) Lower interval of parallel lamination

(e) Graded interval

This sequence is known as the "Bouma Sequence" and illustrates a fining-upward sequence. This sequence also indicates a vertically decreasing flow regime (Harms and Fahnestock, 1965) plus a reduction in the rate of deposition from suspension, with a concommitant increase in the amount of deposition by traction.

A wide variety of basal scour features occur, including: grooves, flutes, longitudinal ridges which are indicative of the erosive nature of these flows.

GRAIN FLOWS.

The concept of grain flow arose from theoretical and experimental work by R.A. Bagnold (1954, 1956). Bagnold reported to have experimentally measured a displacive force generated after a concentration of cohesionless grains was sheared. This force which Bagnold called "dispersive pressure", results in the upward displacement of the grains against the force of gravity, ultimately reducing the yield strenth of the granular mass. Downslope movement will begin and continue until the gravitational force is overcome by the yield strength of of the mass. Flows of this type require very high angles of slope in order to sustain the dispersion necessary for movement. Bagnold (1973) and Francis (1973) report that inertial-dominated grain flow require slopes of 32^0, however, those dominated by the viscous regime require a slope of 37^0 (Bagnold, 1973; Middleton and Hampton, 1973, 1976).

Grain flow deposits are characteristically sharply bounded, ungraded sandstones (Stauffer, 1967). Basal contacts occasionally show peculiar sole markings. When present

lithologic rip-up clasts are randomly dispersed throughout the bed.

Another type of grain flow exists and has characteristics similar to those derived from the true grain flows (described above). Middleton (1969) referred to these flows as "modified grain flows" in which the force sustaining sediment dispersal and movement is derived from an external source. Modified grain flows were called "fluxoturbidites" by Dzulynski *et al.* (1959), a term which has failen into disuse and replaced by the terms "traction carpet" (Bagnold, 1973; Carter, 1975; Lowe, 1982). or "dispersions" (Davies and Walker, 1974; Johnson and Walker, 1979; Hein, 1982a). Flow of this type derive the grain shear necessary to maintain the required dispersive pressure from the shear stress generated by the overriding turbidity current.

LIQUIFIED FLOWS.

A liquified flow is created when a metastable or underconsolidated sediment mass experiences a sudden loss of shear strength due to a framework collapse in response to a temporary increase in pore pressure (Lowe, 1975). Dispersed sediment grains become supported by the upward flow of pore fluids. This may sufficiently reduce yield strength enabling downslope movement, on slopes of 3^{0} - 10^{0} (Middleton, 1969). Sediment-gravity flows of this type are only short-lived. Middleton and Hampton (1973,1976) and Lowe (1975) both report that persistence of liquifaction of fine sand is on the order of a few hours and decreases with increasing grain size. Dissipation of excess pore pressure by pore fluid loss results in the restoration of a rigid sediment framework and the cessation of flow (typically from the base upward).

Sedimentary structures preserved in liquified flows form either during the last stages of sediment movement or during re-sedimentation and water escape from a static bed (Lowe, 1976). Classic dewatering structures typify these deposits plus a wide array of internal deformation and injection structures (Blatt *et al.*, 1980). Post-depositional reworking may produce stratification at the upper boundary of the bed (Lowe, 1976; Hein, 1982a).

DEBRIS FLOWS.

Debris flow refers to a sluggish movement of granular solids (*eg.* sand grains, boulders), clay and water in response to the gravitational pull (Middleton and Hampton, 1973, 1976). Granular solids are "floated" within a clay-water matrix with a density around 2.0 - 2.5 g/cm^3 (Curray, 1966; Middleton and Hampton, 1973, 1976). Hampton (1975, 1979) experimentally showed that with increasing grain size the concentration of the clay-water mixture increases. Finest sands are capable of moving as debris flows with bulk clay content as low as 2 wt.%. Coarsest sand sediment can move as debris flows if they contain 19 wt.% clay or less. The competence of the matrix is a measure of the largest supported grain size, and is controlled by the strength and density of the clay-water mixture (dispersive pressure playing a less important role). Movement of this type of sediment-gravity flow is aided by the low hydraulic permeability of the clayey matrix. This effectively reduces the settling velocity of the granular sediment, enabling the development of sufficient momentum for continued downslope movement (Morgenstern, 1967). Debris flows are capable of sustained movement even on very shallow slopes (Curray, 1966).

Deposition from debris flows occurs by mass emplacement when the driving force, gravity, is exceeded by the yield strength of the debris flow. Deposits are characteristically poorly-sorted ((disorganized fabric (Crowell, 1957; Fisher, 1971)), commonly showing out-sized clasts randomly distributed throughout a fine-grained matrix. This seemingly universal concept of debris flow deposits has since been modified to include internally graded beds (both normal and inverse types)(Hampton, 1972, 1975, 1978). Fully-graded debris flow deposits are the result of the migration of the "rigid plug" boundary within the actively moving debris (the rigid plug refers to the undeformed region within all debris flows)(Hampton, 1975; Nemec, *et al.*, 1980). Lowe (1981), reports that normal grading may also be the product of differential settling of coarse clasts through an insufficiently competent matrix. However, this model can not be used to explain inversely graded beds. Commonly at the base of many debris flow deposits is a thin basal zone of inverse grading. This feature reflects basal shear with the development of significant dispersive pressure (Fisher, 1971). Lower bed contacts are flat or slightly scoured, but in rare cases may be channelled (Pierson, 1980). Upper

contacts are commonly irregular with protruding large clasts or grains.

Mass movements are also important resedimentation processes for the transport of coarse sediment into the deep-sea. Unlike sediment-gravity flows, mass movements are characterised by the maintenance of the original internal structure within the "pre-slide" sediment pile (at least to some recognizable degree).

SLUMPS AND SLIDES.

Slumps and slides refer to mass movements in which the elastic limit of the sediment has not been exceeded (Dott, 1963; Nardin, *et al.*, 1979). Movement occurs along discrete internal shear planes when the strength force (that which resists deformation) of an inclined sediment pile is overcome by the gravitational force. Submarine slumps and slides are capable of movement on slopes with gradients of only 0.5° (Grant-Mackie and Lowry, 1964). Slide deposits show only minor internal deformation, typically confined to a narrow region at the base of the bed. Original sedimentary structures are typically well preserved. Slumps on the other hand show greater internal deformation. Extreme deformation is indicated by the occurrence of elongated pieces of remnant bedding "floating" in a mud or sand matrix. Deposits typically exhibit slump folds whose axial planes are oriented downslope (Helwig, 1970). However, study of a snow slump (Lajoie, 1972) indicates that the orientation of fold axis depends on the position within the slump. In the centre of the slump where faulting is common fold axis lie at very high angles to the downslope trend. Toward the edges of the slump parallelism with the downslope trend improves. Basal contacts of both slumps and slides represent a decollement zone and lack the erosional surfaces typical of other sediment-gravity flow deposits.

C. FACIES SCHEME

Individually measured beds have been divided into the following sedimentary facies, using the Udden-Wentworth grain-size scale for facies description. This is similar to the approach used by Davies and Walker (1974). Size intervals refer to the average ten-largest clasts per bed (referred to in the text as D(10)).

(i) cobble / coarse pebble conglomerate: 15-90 mm.

(ii) fine pebble conglomerate / granule sandstone: 0.5-15 mm.

Beds showing internal stratification were placed in facies based on stratification type.

In this study, only abundant facies are described below. Rare partings of slate and fine-grained sandstone are not discussed in the following facies scheme and are referred to in the text and on the drafted measured sections (Appendix VI) as "sl","ss" or "slss" (combination of the two).

Basal bedding contacts were described as flat, undulose, scoured or channelled and are related to the depth of penetration of the overlying bed into the underlying bed(s). Flat contacts show no evidence of erosion, forming a smooth contact with the underlying bed. Undulose contacts are characteristically wavy, with scour depths usually less than 5 cm. Scoured contacts are irregular surfaces with scour depth less than 50 cm . Channellized contacts are those with scour depth greater than 50 cm (Figure 17). In extreme cases these can reach several metres (Figure 18). Loaded bedding contacts are also included. Unlike most of the previously discussed contacts, loaded contacts are not related to an erosive event, but are simply shallow (less than 5 - 8 cm) deformational features (Figure 19). In the absence of upper-bed stratification, loading is difficult to differentiate from undulose and some scoured contacts.

The term "structureless" herein follows the useage of Hein and Walker (1982), and applies to those beds showing some type of grading, but are devoid of traction sedimentation structures. The term "massive" applies to beds showing no grading or tractional features.

FIGURE 17: Small-Scale Channelled Contact.

FIGURE 18: Large-Scale Channelled Contact.

FIGURE 19: Loaded Contact.

D. FACIES DESCRIPTIONS (FACIES 1 - 12)

FACIES 1: CHAOTIC CONGLOMERATE AND SLATE MIXTURE/SLIGHTLY DISRUPTED-BEDDED PEBBLY SANDSTONE AND SLATE.

General Features:

Beds of chaotic conglomerate and slate mixtures (Figure 20) are very common at Bath Creek Quarry comprising 8% of the total measured section. Average bed thickness is 0.96 m (range: 0.17 m to 3.0 m). At Redoubt Mountain these beds are less common accounting for 2% of the measured section with an average bed thickness of 0.86 m (range: 0.18 m to 2.67 m). Thicker beds at both localities are characterised by larger slate intraclasts and the average size of the ten-largest clasts (D(10)).

Also included in this facies are slightly disrupted bedded pebbly sandstone and slate beds (Figure 21). These beds are found exclusively at Redoubt Mountain comprising only 0.07% of the measure section. Beds are invariably thin with an average thickness of 0.19 m (range: 0.18 m to 0.21 m).

Internal Features:

Beds of chaotic conglomerate and slate mixtures are typically disorganized in appearance. Coarse granular material, usually of fine to medium-pebble size, is dispersed throughout a medium to coarse-grained sandstone matrix. The most characteristic feature is the random dispersal of contorted to uncontorted slate intraclasts throughout the beds. These intraclasts show no preferred orientation or imbrication. Although beds are massive, some small-scale sedimentary structures can be identified. Overturned folds, typically restricted to the basal regions of beds are occasionally observed. Basal bed contacts are typically flat, irregularly scoured or in rare cases deeply channelled. Thickly-bedded units usually possess the more erosive types of basal contacts.

The slightly disrupted bedded pebbly sandstone and slate beds are phenotypically different from those just described. These beds are characterised by a thin contorted,

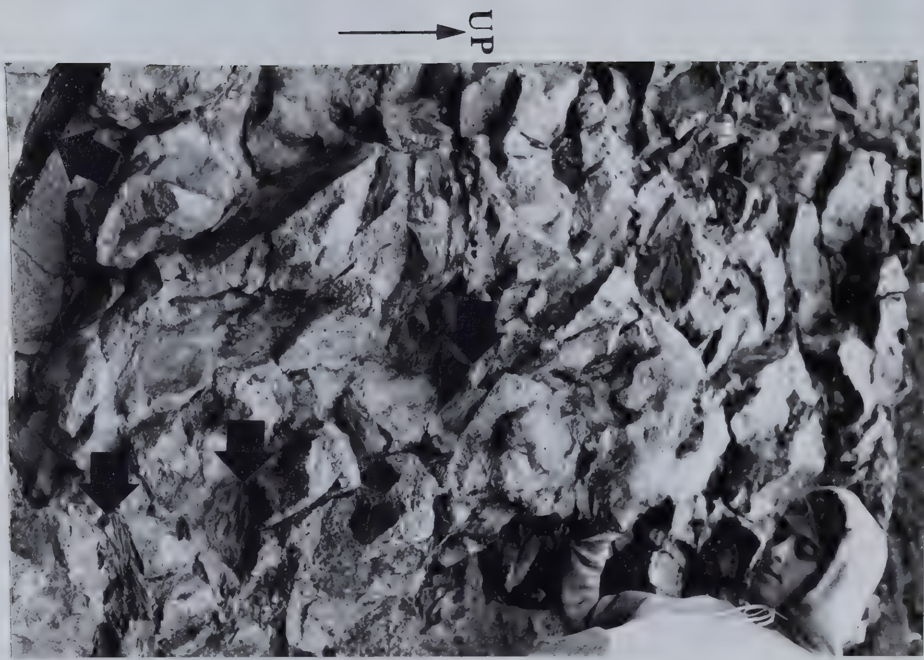


FIGURE 20: Facies 1: Chaotic Conglomerate and Slate Mixture (arrows point to slate intraclasts).

FIGURE 21: Facies 1: Slightly Disrupted-Bedded Pebbly Sandstone and Slate. (lower arrow points to fragmented basal layer, upper arrow points to undisturbed stratification in the upper part of the bed)

often fragmented basal layer, abruptly overlain by a thicker uncontorted parallel-bedded layer. Capping this upper undistrubed layer is a rare thin (less than 1 cm) convolute laminated layer. Basal bedding contacts are invariably regular and flat.

FACIES 2: DISORGANIZED, DISPERSED PEBBLY CONGLOMERATE/PEBBLY SANDSTONE.

General Features:

This facies comprises 0.8% of the total measured section at Bath Creek Quarry with an average bed thickness of 0.31 m (range: 0.09 m to 0.44 m). At Redoubt Mountain it comprises 12% of the measured beds with an average bed thickness of 2.8 m (range: 0.53 m to 4.5 m).

Internal Features:

Facies 2 beds are massively bedded and characterised by the random distribution of fine-pebble (Figure 22) to cobble-sized clasts within a fine to coarse-grained sandstone matrix. In the coarser-grained beds out-sized clasts, typically of coarse-pebble to fine-cobble size are commonly observed (Figure 23). Large contorted to uncontorted slate and less common mudstone intraclasts are often found in the upper units of the beds. Basal contacts are undulose to slightly scoured, and in only one locality, channelled.

FACIES 3: GRADED, MATRIX-SUPPORTED COBBLE/COARSE PEBBLE CONGLOMERATE.

General Features:

This facies is the most common facies at Redoubt Mountain comprising 31% of the measured section. At Bath Creek Quarry Facies 3 is the second most common facies accounting for 19% of the measured beds. Bed thickness averages 2.1 m (range: 0.09 m

FIGURE 22: Facies 2: Fine-Grained, Dispersed Pebbly Conglomerate / Pebbly Sandstone.

FIGURE 23: Facies 2: Coarse-Grained, Dispersed Pebbly Conglomerate / Pebbly Sandstone.

to 4.3 m) at Bath Creek Quarry and 1.3 m (range: 0.18 m to 4.85 m) at Redoubt Mountain. Beds of this facies are characterised by a D(10) of coarse-pebble to cobble clasts.

<u>Internal</u> <u>Features:</u>

Facies 3 is typified by poorly-sorted, structureless, thickly-bedded units in which coarse-pebble and cobble clasts are supported within a medium to coarse-grained sandstone matrix (Figure 24). Normal grading, primarily of the "coarse-tail" type with lesser "distribution" grading (Middleton, 1967) predominates with only minor inverse or inverse-to-normal grading.

Due to the matrix supported nature of this facies, individual clasts weather out poorly and are difficult to use for imbrication studies. Basal contacts are typically planar, undulose or loaded; less common scoured and rare channelled types occur.

FACIES 4: GRADED, MATRIX-SUPPORTED FINE PEBBLE CONGLOMERATE / GRANULE SANDSTONE.

<u>General</u> <u>Features:</u>

This facies is the most common at Bath Creek Quarry comprising 42% of the total measured section. At Redoubt Mountain Facies 4 beds comprise 15% of the total measured section. Average bed thickness is 0.94 m (range: 0.1 m to 3.36 m) at Bath Creek Quarry and 0.77 m (range: 0.18 m to 4.56 m) at Redoubt Mountain. Beds of Facies 4 are characterised by a D(10) of granule to fine-pebble clasts.

<u>Internal</u> <u>Features:</u>

Facies 4 consists of poorly-sorted structureless, normally graded beds in which the clasts are supported within a medium to coarse-grained sandstone matrix (Figure 25). Coarser more thickly-bedded units commonly show "coarse-tail" grading and possess undulose or slightly scoured basal contacts. Finer more thinly-bedded units typically show "distribution" grading with flat, undulose and loaded basal contacts.

FIGURE 24: Facies 3: Graded, Matrix-Supported Cobble / Coarse Pebble Conglomerate.

FIGURE 25: Facies 4: Graded, Matrix-Supported Fine Pebble Conglomerate / Granule Sandstone.

FACIES 5: GRADED, CLAST-SUPPORTED COBBLE / COARSE-PEBBLE CONGLOMERATE.

General Features:

This facies is far more common at Redoubt Mountain comprising 12% of the total measured section, compared with only 4% at the Bath Creek Quarry. Beds found at both study locations are characteristically thickly-bedded, averaging 1.67 m (range: 1.64 m to 1.7 m) at Bath Creek Quarry and 1.5 m (range: 0.6 m to 3.7 m) at Redoubt Mountain with a D(10) of coarse-pebble to cobble clasts.

Internal Features:

The distinctive feature of this facies is a poorly-sorted, clast-supported framework with interstitial spaces filled with medium to coarse-grained sandstone (Figure 26). Beds are structureless, thickly-bedded and commonly normally graded. Normal grading is typically abrupt or of the "coarse-tail" type (rarely of the "distribution" type). However, inverse and inverse-to-normal grading does occur more commonly in beds of this facies than any other in the study. Some beds show a well-developed clast "a-axis" imbrication with only minor "b-axis" imbrication. This fabric is most pronounced in the coarse-grained beds at Redoubt Mountain where clasts are well-exposed and can be easily measured for imbrication studies. Basal bedding contacts are always erosive in appearance with scoured, or deeply-incised channelled types.

FACIES 6: GRADED, CLAST-SUPPORTED FINE PEBBLE CONGLOMERATE / GRANULE SANDSTONE.

General Features:

Facies 6 comprises 7% of the beds at Bath Creek Quarry and 8% at Redoubt Mountain. Average bed thickness is 0.83 m (range: 0.24 m to 3.15 m) at Bath Creek Quarry and 0.73 m (range: 0.27 m to 1.42 m) at Redoubt Mountain with a D(10) of granule to fine-pebble clasts.

FIGURE 26: Facies 5: Graded, Clast-Supported Cobble / Coarse-Pebble Conglomerate.

Internal Features:

Beds of facies 6 are invariably poorly-sorted and structureless with normal-grading of the "distribution" type and less common "coarse-tail" type (Figure 27). Basal bed contacts are undulose or scoured.

FACIES 7: GRADED PEBBLY/SANDY TURBIDITES.

General Features:

Facies 7 is a distinctive facies and of key importance to the paleogeographic reconstruction of the area. This facies comprises 9% of the total measured section at Bath Creek Quarry and 19% at Redoubt Mountain. The marked difference between the two study areas is largely due to the thick upper slate/turbidite horizon (average thickness: 13 m) found at Redoubt Mountain, which is mostly covered at the Bath Creek Quarry, making estimates of its total thickness impossible. A lower slate/turbidite horizon is observed at both study locations, but only delimits the stratigraphic base of the study and is not included in the measured sections.

Bed thickness is directly-related to grain size. Coarse-grained beds with D(10) of coarse pebble-size, are typically thickly-bedded, averaging 1.0 m. Finer-grained beds with a maximum D(10) of granule-size, or more typically coarse and medium-grain sandstone are more thinly-bedded, averaging 0.1 m.

Internal Features:

Beds of Facies 7 all possess some type of grading. Thick, poor to moderately well-sorted coarse-grained beds usually show "distribution" normal grading with only minor inverse or inverse-to-normal grading. Thin, moderately to well-sorted, fine-grained beds are all normally graded of the "distribution" type.

The distinctive feature of Facies 7 is the presence of Bouma turbidite divisions (Bouma, 1962). Thick, coarse-grained beds typically show Bouma (AB) divisions, but rarely show Bouma (ABCD) divisions (Figure 28). Thin, fine-grained beds commonly show upper Bouma divisions (BCD, CD) and occasionally near complete Bouma turbidites (ABCD) (Figure

FIGURE 27: Facies 6: Graded, Clast-Supported Fine Pebble Conglomerate / Granule Sandstone (only the base of a Facies 6 bed is shown).

29).

Paleocurrent directions were measured on exposed "C" division ripple sets as well as from oriented samples selectively taken from the parallel laminated "B" division. Basal bedding contacts are only slightly to non-erosional. Coarse-grained beds are moderately scoured to flat, fine-grained beds are undulose to flat. Other types of basal contact features are common in beds of this facies. Loading is commonly observed and typically well defined. Flame structures (Figure 30), flutes, grooves and flow structures: overturned folds (Figure 31) and basal drag folds (Figure 32) (Prentice, 1960) were also observed.

FACIES 8: UNGRADED COBBLE/GRANULE SANDSTONE.

General Features:

Beds of this facies comprise 7% of the measured section at Bath Creek Quarry with an average bed thickness of 0.87 m (range: 0.33 m to 1.88 m). At Redoubt Mountain 4% of the beds are represented by this facies, averaging 0.74 m in thickness (range: 0.12 to 2.67 m). Beds of Facies 8 encompass a wide range of D(10) clast size. Very coarse-grain beds with a D(10) of cobble-size clasts contain the largest clasts found in the study (180 mm). Fine-grained beds show a D(10) of granule-size or finer (coarse or medium-grained sandstone).

Internal Features:

Beds of facies 8 are characteristically massive with no internal stratification or grading. Very coarse-grained beds consist of cobble to pebble-size clasts with a coarse and medium-grained sandstone interstitial fill (Figure 33). Basal contacts are always very erosive. Scours, or often deeply incised channels floor these coarse-grained beds. Finer-grained beds consist of medium to coarse-grained sandstone, occasionally with a random dispersal of granule to pebble-sized clasts throughout (Figure 34). Basal contacts are flat to irregularly scoured, and in rare cases injected (Figure 35).

FIGURE 28: Facies 7: Thickly-Bedded Graded Pebbly / Sandy Turbidites.

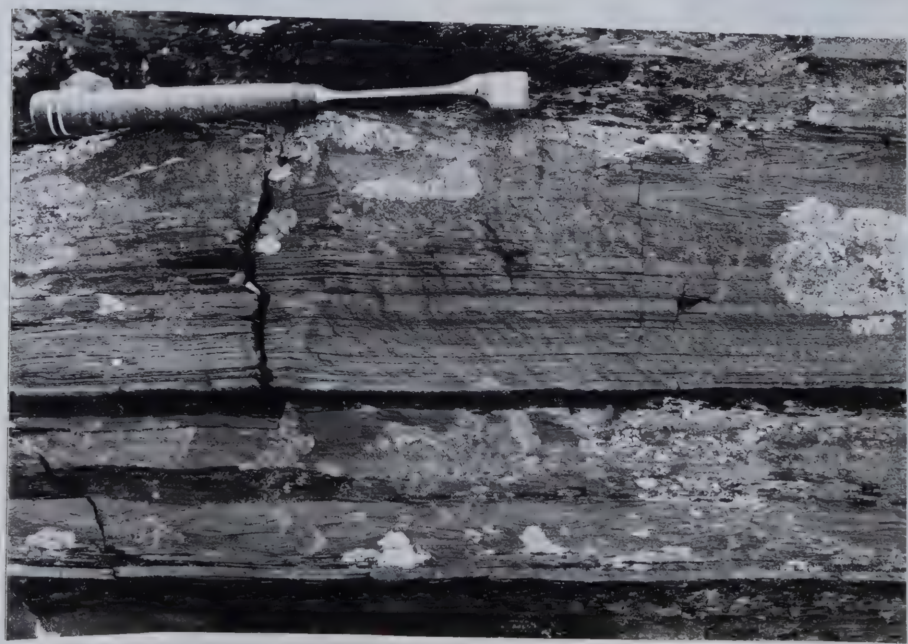


FIGURE 29: Facies 7: Thinly-Bedded Graded Pebbly / Sandy Turbidites.

FIGURE 30: Flame Structures (arrows point to individual "flames" which have been injected into the overlying turbidite bed).

FIGURE 31: Overturned Folds (arrow points to overturned fold within a turbidite "C-division").

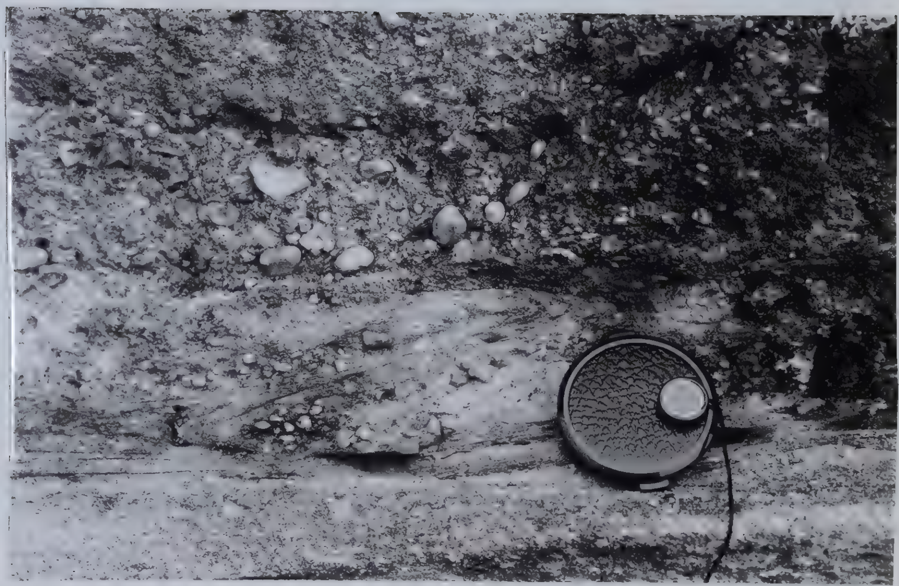


FIGURE 32: Drag Fold. This feature is within the inversely graded portion of a inverse-to-normally graded turbidite "A-division".

FIGURE 33: Facies 8: Coarse-Grained, Ungraded Cobble / Granule Sandstone.

FIGURE 34: Facies 8: Fine-Grained, Ungraded Cobble / Granule Sandstone.

FIGURE 35: Basal Injection Feature Beneath a Fine-Grained Facies 8 Bed.

FACIES 9: GRADED / TROUGH CROSS-BEDDED OR WAVY-BEDDED CONGLOMERATE AND SANDSTONE.

General Features:

Facies 9 accounts for 4% of the beds at Bath Creek Quarry and 2% at Redoubt Mountain. Average bed thickness at Bath Creek Quarry is 0.76m (range: 0.3 m to 1.2 m) and 1.2 m (range: 0.26 m to 2.17 m) at Redoubt Mountain. Average D(10) clast size is usually pebble-size or finer but occassional cobble clasts are observed.

Internal Features:

All the beds of Facies 9 are normally graded of the "distribution" type. The most important feature of this facies is the presence of trough cross-bedding (Figure 36 and 37) or wavy-bedding (Figure 38 and 39), found exclusively in the uppermost sandstone of the graded beds. Trough cross-bedding is confined to isolated sets ranging in height from 6 cm to 17 cm at Bath Creek Quarry and 16 cm to 32 cm at Redoubt Mountain. Wavy sets are rare and are only observed at Bath Creek Quarry. Wavy-bedding produces a very regular "sinusoidal" profile that is continuous across the upper bed surface. Wavy form-sets are rarely internally stratified with gently undulating laminae conforming to the shape of the "wave".

Basal contacts are highly variable, consisting of flat, irregularly scoured or rare channelled types.

FACIES 10: UNGRADED / TROUGH CROSS-BEDDED CONGLOMERATE AND SANDSTONE.

General Features:

This facies makes up 3% of the total measured section at Bath Creek Quarry and only 0.2% at Redoubt Mountain. At Bath Creek Quarry beds of this facies are composed of stacked lens-shaped sets with an average height of 0.77 m (range: 0.26 m to 1.33 m) (Figure 40). At Redoubt Mountain beds of Facies 10 are only single form-sets with an

FIGURE 36: Facies 9: Graded / Large-Scale Trough Cross-Bedded Conglomerate and Sandstone.

FIGURE 37: Facies 9: Graded / Small-Scale Trough Cross-Bedded Conglomerate and Sandstone.

FIGURE 38: Facies 9: Graded, Wavy-Bedded Conglomerate and Sandstone.

FIGURE 39: Facies 9: Graded Wavy-Bedded Conglomerate and Sandstone. Photo shows the upper bedding surface of the bed.

FIGURE 40: Facies 10: Ungraded / Trough Cross-Bedded Conglomerate and Sandstone. Shown in the photo are a number of superimposed lensoid-shaped bedforms.

average thickness of 0.36 m (range: 0.19 m to 0.53 m).

Internal Features:

Stacked lens-shaped sets at Bath Creek Quarry occasionally show internal trough cross-laminations, but usually appear massive due to the homogeneity of the sediment. At Redoubt Mountain beds of facies 10 are single trough cross-bedded form-sets showing fining upward within the laminae. Basal contacts at both locations are flat to undulose.

FACIES 11: LINSEN-BEDDED TROUGH CROSS-BEDDED SANDSTONE IN FINE-GRAINED SANDSTONE.

General Features:

This very rare facies comprises only 0.2% of the beds at Bath Creek Quarry and is restricted to only one observed occurrence at Redoubt Mountain. Average bed thickness at Bath Creek Quarry is 0.10 m (range: 0.04 m - 0.14 m) and 0.36 m at Redoubt Mountain.

Internal Features:

Facies 11 is characterised by coarser-grained trough cross-bedded form-sets embedded within a finer-grained, parallel laminated sandstone. At Bath Creek Quarry trough cross-bedded units (D(10) of granule-size), erosively overlie and are blanketed by fine-grained, parallel laminated sandstone (Figure 41). At Redoubt Mountain the fine-grained sandstone bed is scoured out and filled with trough cross-bed scour fills. These erratically superimposed fills are all normally graded and have a D(10) of fine-pebble clasts. Basal contacts of the fine-grained sandstone is always sharp and flat.

FACIES 12: UNGRADED STRATIFIED PEBBLY/GRANULE SANDSTONE.

This facies is rare, accounting for only 0.8% of the beds at Bath Creek Quarry and 0.2% at Redoubt Mountain. Beds are well-sorted, thinly-bedded; averaging 0.2 m (range: 0.085 m to 0.75 m) and parallel-laminated. Each bed is actually a composite comprised of

FIGURE 41: Facies 11: Linsen-Bedded Trough Cross-Bedded Sandstone in Fine-Grained Sandstone. Arrows Point to Parallel-Bedded Fine-Sandstone.

several thin, parallel beds. In one petrographic thin section cut perpendicular to bedding, normal grading was observed within the individual thin beds. Bedding contacts of each thin bed are always sharp and flat.

A summary of the distribution of the twelve sedimentary facies reported at the two study areas is given in Figure 42.

E. DEPOSITIONAL MECHANISMS

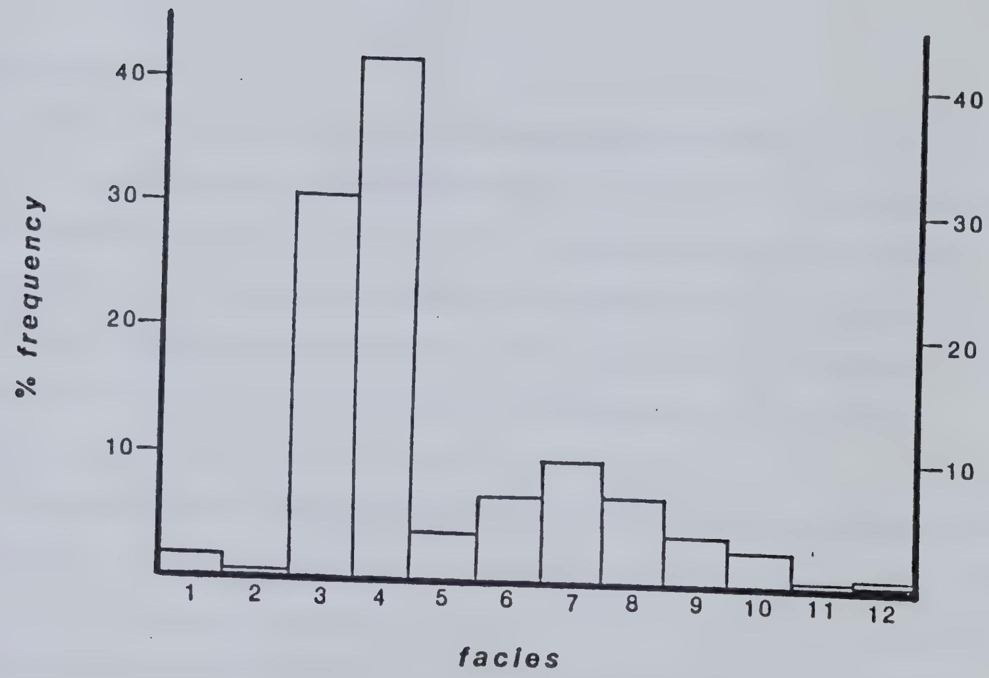
FACIES 1.

Beds of Facies 1 are products of mass movement. Slightly disrupted-bedded pebbly sandstones and slate are interpreted as slide deposits. The base of these beds represents a decollement or slide plane, overlain by a zone of disrupted, distorted or often fragmented bedding. This deformed zone is the product of high frictional shear stress generated at the underlying (undeformed) bed / slide interface. Increasing deformation in this zone is directly-related to increased shear. Above the disturbed zone is a thicker region of parallel bedded slate and sandstone, representing the original undeformed stratification of the "pre-slide" sedimentary pile. Rarely, this zone is capped by a thin (less than 1 cm) convoluted layer. Deformation in this uppermost part of the bed represents the development of significant interfacial shear stress with the overlying ambient fluid (sea-water).

Chaotic conglomerate and slate mixtures are interpreted as slump deposits. Similar to slide deposits in depositional process, slump deposits are characteristically more chaotic in appearance. Internal slump folds (typically illustrated by folded slate intraclasts), plus the chaotic distribution of large uncontorted to contorted slate intraclasts within a disorganized pebbly-sandstone matrix, indicates a greater degree of internal deformation

SUMMARY OF FACIES DISTRIBUTION

BATH CREEK QUARRY



REDOUBT MOUNTAIN

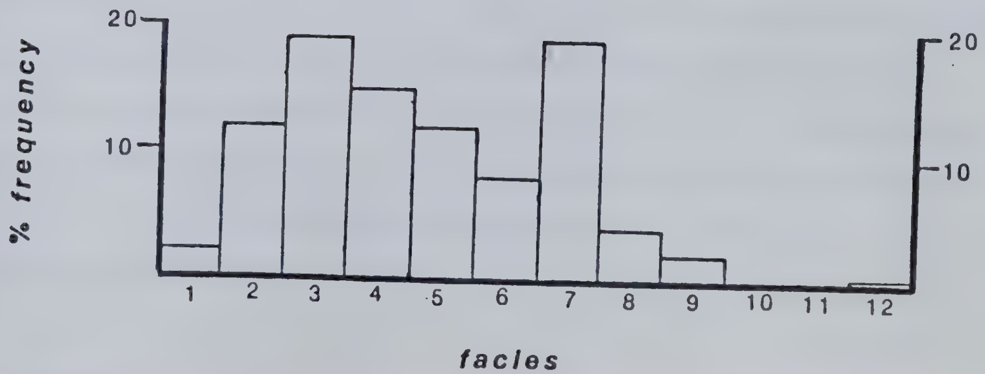


FIGURE 42.

than that indicative of slide deposits.

Slides and slumps are elastic, non-erosive mass movements possessing flat and regular basal contacts. Rare erosive basal features such as scours and channels are not a product of their movement, but that of an earlier erosive current.

FACIES 2.

Beds of Facies 2; disorganized, dispersed pebbly conglomerate / pebbly sandstone are interpreted as subaqueous debris flow deposits. These beds are characterised by the random distribution of clasts (often "out-sized") within a finer-grained matrix. Beds composed of relatively equal-sized clasts appear to have a less chaotic appearance than those with diverse clast sizes. This difference is probably related to the degree of coarse clast sorting during deposition of the original sediment pile, prior to debris flow resedimentation.

Typically, Facies 2 debris flow deposits possess a disorgananized fabric (Appendix I(i): Figures 50 (d),(f)), a consequence of poor grain mobility during flow (Lindsay, 1968). This can be attributed to the presence of a highly concentrated viscous matrix composed of mud and crypto-crystalline quartz. The matrix provides strength to the flow and buoyancy for supporting coarse clasts above the non-moving bed. In rare cases however beds possess a well developed clast fabric (Appendix II(ii): Figures 51 (d),(h),(k); Appendix II(iii): Table 3). Variability in the strength of internal clast fabric may be related to processes affecting fabric development. Lindsay (1968) showed experimentally that during flow in which viscous effects dominated, the development and subsequent destruction of a well-defined clast fabric was a cyclic process. Therefore, flows which were arrested at different instances within the "clast cycle" would show varying degrees of fabric development. Other parameters such as flow velocity and viscosity are also of great importance since they affect the rate of clast mobility within the flow. As a result, paleocurrent information derived from beds deposited from debris flows should be treated with extreme caution.

Large contorted and uncontorted slate and less common mudstone clasts, are generally confined to the upper regions of the bed and are thought to represent a rigid plug rafted along near the top of a subaqueous debris flow. Debris flow basal contacts are typically unabraided. Scoured and rare channelled contacts are probably the result of earlier more erosive flows, but may be a product of their own basal scouring.

Another possible mechanism may explain the deposition of Facies 2 beds. Lithologies similar to those described by Facies 2 have been previously reported in deep-marine environments by Hein (1982a). These beds were interpreted as high concentrated dispersion deposits where hindered settling effects prevent the development of grading. However, Coulson and Richardson (1955, 1968) point out that in concentrated suspensions where grain size varies by more than 6:1 (such is the case for many Facies 2 beds) larger grains settle faster than smaller ones. This would ultimately produce normal grading in coarse-grained beds, while finer-grained beds (those finer than 6:1) would remain massive. As a result it is believed that the disorganized relatively fine-grained Facies 2 beds may be related to high concentrated dispersions associated with turbidity currents, but the coarse-grained beds are as indicated above, debris flow deposits.

FACIES 3 and 4.

Beds of both Facies 3 and 4 are characterised by graded, matrix-supported conglomerate, typically poorly-sorted and structureless. Matrix-rich conglomerates of this type have been reported rarely in the literature. This may not be because of their rarity in the geologic record, but a consequence of poor bed interpretation related to our limited understanding of the depositional mechanisms of this type of conglomerate.

Beds of these facies are interpretated as subaqueous debris flows. Downslope movement of these beds is primarily due to the upward support of coarse granular material within a buoyant matrix of medium and coarse-grain sand. Dispersive pressure and fluid turbulence are poorly-developed because of the high concentrated nature of these flows. Ubiquitous grading within the beds points to some degree of internal grain clast

mobility, differentiating them from process similar beds described by Facies 2. Development of normal grading is believed to be a result of the continual movement of the rigid plug boundary within the flow (Hampton, 1975). Inverse-to-normal grading indicates a zone of basal shear and the development of dispersive pressure. Beds that are inversely graded throughout are deposited by flows in which the rigid plug extends to the top of the flow at all times (Hampton, 1975).

Normal grading may also be explained by hindered settling effects associated with high concentated dispersions. As previously mentioned this type of grading may develop in dispersions where particle sizes vary by more than 6:1 (Coulson and Richardson, 1955, 1968). Hein (1982a) utilizes hindered settling effects to explain abrupt normal grading in deep-sea clast dispersion deposits. However, most Facies 3 and 4 beds are not graded in this manner and are therefore thought not to be process related. Also, Crowe and Fisher (1973) point out that upon deceleration of a sedimentary dispersion and shortly before deposition, there is a rapid increase in flow density and viscosity. This effect would drastically reduce the settling velocity of the coarse clasts, thereby preventing the development of good progressive grading (a feature common in Facies 3 and 4 beds).

Inverse grading may be explained by the upward movement of coarse-grained clasts because of their reduced density compared to the finer fraction of the high concentrated suspension (fine fraction produces a dense medium). With the downward settling of finer-grained sediment through the interstitial spaces between coarser grains inverse grading by the kinetic sieve effect would develop (Middleton and Southard, 1977). However, this mechanism can not explain the development of inverse-to-normal grading, a feature present in some Facies 3 and 4 beds. For this reason plus the paleogeographic setting of the two study areas (to be discussed in Chapter 4) a debris flow origin for these beds is still favoured.

Typically diverse clast long-axis orientations within the lower portions of coarse-grained beds (Appendix I(i), Figure 50(g)), are probably features related to the time of individual flow termination. In rare instances however, well-developed "a-axis" and less common "b-axis" imbrication is observed. "A-axis" imbrication is similar to fabric patterns in flows where viscous effect dominate (Lindsay, 1968) however "b-axis" imbrication is more difficult to explain, but has been reported in laminar debris flows (Johnson, 1970 in

Hein, 1982a) and lava flows (Khan, 1962).

Deep erosive channelled contacts typically associated with beds of Facies 3, and scoured and undulose contacts of Facies 4, indicate a depositing flow of high velocity and density. Erosive flows of this type are restricted to areas of high slope (Pierson, 1980), and particularly in subaqueous environments, in close proximity to their source.

FACIES 5 and 6.

Facies 5 and 6 are characterised by graded, clast-supported conglomerate. Lithologies are typically poorly-sorted and structureless. Coarse-grained beds of Facies 5 typically show abrupt or "coarse-tail" normal grading with less common inverse and inverse-to-normal grading types. Facies 6 beds are characteristically finer-grained and show an enhanced proportion of "distribution" normal grading and less common abrupt and "coarse-tail" grading. Beds of this description are the product of rapid suspension deposition from poorly-stratified flows, closely resembling those described as large-scale "proximal" turbidites (Walker, 1967).

Fluid turbulence is an active supporting mechanism in the flows depositing beds of these facies. The presence of ubiquitous grading, occassional well-developed "b-axis" imbrication and the erosive nature of basal bedding contacts (extreme in some cases) indicates the active presence of fluid turbulence. Well-developed "a-axis" parallel and imbricated upstream orientations, occasionally found in the coarse-grained basal region of graded beds (Appendix I(i): Figure 50(i); Appendix I(ii): Table 2) and commonly in the upper-bed sandstones (Appendix II(ii): Figure 51 (c),(f),(i); Appendix II(iii): Table 3) indicates the co-existance of clast dispersions supported by dispersive pressure (Rees, 1968). Grains aligned in this manner are statistically most stable, because grain collisions generate forces that are "directed along the principal axis of the clast ellipse, and hence no rotational couple" (Davies and Walker, 1974). Preservation of this fabric implies direct suspension deposition with no post-depositional bed-load movement.

Beds described by these facies are believed to be *en masse* deposits of large clast dispersions, where clasts were supported by a combination of dispersive pressure and to

a lesser extent fluid turbulence (Middleton and Hampton, 1973,1976). These deposits are associated with turbidity current activity in the deep-sea, commonly the base-of-slope environment (Hein, 1982a), and are referred to as "modified grain flows" (Middleton and Hampton, 1973,1976). A thin basal concentration of coarse clasts, approximately 5 cm or so (Hein, 1979,1982a; Lowe, 1983), is dispersed by shear stress generated by an overriding turbidity current. Thickly-bedded units of Facies 5 and 6 represent aggrading "piecemeal" deposition from this thin basal dipersion (Hein, 1982a).

Beds of Facies 5 are characterised by "coarse-tail" grading. This type of grading indicates rapid deposition from highly concentrated flows possessing poor internal stratification (Middleton, 1967; Hein, 1982a). Facies 6 beds are deposited by better stratified flows, indicated by the more common occurrence of "distribution" grading.

FACIES 7.

Facies 7 beds are typical moderate to well-sorted Bouma turbidites (Bouma, 1962). Deposition was from moderate to well-stratified turbid flows in which both traction (bed-load) and dispersion transport were important. Imbrication peels prepared from turbidite "B" divisions indicate predominant dispersion transport and deposition. However, occassional co-existance of both "a-axis" and "b-axis" imbrications are observed. This condition implies the simultaneous support of sediment by both dispersive pressure and fluid turbulence, an observation previously reported by Middleton and Hampton (1973). Beds possessing rippled "C" or parallel laminated "D" divisions indicate dominant traction transport in the turbidite divisions. Typical beds of Facies 7 consist of ABCD, BCD, AB, AC, CD Bouma divisions. Erosive basal contacts, such as, scours, flutes and grooves lend credence to the turbulent nature of these flows.

Beds of this facies occur on two distinct scales: very rare, greater than 1.0 metre beds and the typical thinner 0.05 metre (average) beds. The former represents very large turbidity currents, probably coincident with a shallower catastrophic event. Thinner-bedded, finer-grained beds typically showing upper Bouma divisions, represent small-scale turbid flows. These flows are probably remnants of larger, coarser-grained

flows arrested in more proximal environments, and not the product of deep water contour-currents or nepheloid flows. They arise as low concentrated entrained fluids, initially moved and "fed" by a larger underriding turbidity current, but which continued to independantly move after the latter has ceased to flow.

FACIES 8.

Beds described by Facies 8 are highly diverse in their external appearance, and equally in their depositional processes. Beds consist of ungraded clast-supported conglomerate or ungraded dispersed pebbly sandstone.

Ungraded clast-supported conglomerate beds are process related to beds of Facies 5 and 6. Large basal clast dispersions maintained by high dispersive pressure are indicated by beds possessing a strong clast "a-axis" parallel and imbricated upstream orientation (Appendix I(i), Figures 50 (a),(c),(h)) however some beds show a more randomly oriented fabric (Appendix I(i), Figures 50 (e),(j)). Variation in clast fabric is probably related to the degree of grain mobility associated with the travelled distance of the flow (analogous to the temporal length of the flow). Well developed fabrics originate from flows which have had sufficient time for dispersive pressure effects to orient the clasts. Poorly-developed fabric is a consequence of insufficient time to create an organized fabric because of very short travel distance. Poor-sorting and the absence of grading within beds of this facies implies limited grain mobiltiy during flow, a result of the supression of fluid turbulence. However, this feature may also be explained by rapid deposition from poorly-stratified turbulent flows. Similar to beds of Facies 5 and 6, Facies 8 clast-supported conglomerate is interpreted as piecemeal, *en masse* deposits from basal dispersions maintained below a large-scale turbidity current. Erosive basal contacts, extreme in some cases, point to the erosive nature of the depositional flows.

Sandstone, dispersed pebbly sandstones and rare clast-supported conglomerate beds are deposited from "pure" grain flows. Parallel orientation and imbrication of coarse clast and sand grain long-axis indicate transport and deposition from flows which were dominated by dispersive pressure. Paleoflow directions from these beds lie at a high angle

to those derived from many of the Facies 8 beds associated with turbidity currents. With the availability of high slopes, these beds are set into motion by the development of dispersive pressure. *En masse* deposition occurs because of decreasing flow competence related to decreasing shear stress. This condition is probably the result of decreased regional slope and the insufficient development of a secondary supporting mechanism. Irregular basal scour and rare injection features illustate the fluidity and high energy of these flows.

FACIES 9.

Beds of Facies 9 are deposits from large-scale turbidity currents. Thick, graded basal regions of each bed pass transitionally upward into a thin cap of trough or wavy cross-bedding. The basal well-sorted, graded part of each bed represents suspension deposition from a well-stratified turbidity current. Upper parts of the beds indicate a period of rapid suspension fallout accompanied with tractional transport.

Medium-scale trough cross-bedding (averaging 0.12 m at Bath Creek Quarry and 0.25 m at Redoubt Mountain) is the remnant sedimentary structure of once actively migrating dune bedforms. The grain-size of the cross-bedded Facies 9 units is usually medium to fine-pebbly sandstone. Using the equations and procedure outlined in Appendix IV, and a friction factor of 0.042 (Simons, *et al.*, 1965), an average flow velocity for dune development in 2 mm. sand is approximately 110 cm/s or greater (uncertainty arises from uncertain bedform boundaries in coarse-grained sediments) Velocity of this magnitude would imply turbidity current association. Transitional contact with the underlying graded portion of the bed also reaffirms a turbidity current interpretation. Trough cross-beds are constructed from reworked bed-top sediments by the "tail" of the turbidity current or the low concentrated entrained layer.

Wavy cross-bedded bed-tops are interpreted as antidune bedforms. Similar features have been documented in flysch deposits of the Cloridorme Formation in Gaspe Quebec (Skipper, 1972). Antidunes are upper flow regime sedimentary structures, and in ancient deep-sea environments are associated with turbidites. Development of antidunes

occurs at a density interface within the turbidity current. Coarse-grained sediment concentrates near the base of the flow, forming a thin (5 cm), significantly more dense fluid layer (Hand, *et al.*, 1972). Shearing at the density interface results in the development of the appropriate flow conditions for antidune construction. Average flow velocities of 120 cm/s to 170 cm/s are necessary for antidune development. Velocities of this magnitude plus the transitional contact with the underlying graded portion of the bed indicates deposition from high velocity turbidity currents.

FACIES 10.

Beds of Facies 10 at Bath Creek Quarry are actually composites of a number of smaller, relatively fine-grained stacked beds. Individual small-scale beds are lensoid in shape which are less commonly internally trough cross-bedded. Beds at Redoubt Mountain are comprised of single coarse-grained, trough cross-bedded form-sets. These beds are laterally continuous across the outcrop, with length dependant on outcrop width. Each lensoid bed at Bath Creek Quarry or single trough cross-bedded form-set at Redoubt Mountain is interpreted as the deposit or scour fill from an individual migrating dune bedform.

Beds comprised of stacked dunes imply a period(s) of rapid sediment input accompanied with rapid dune migration and deposition. Single form-set beds imply very rapid deposition from a short lived, high velocity flow. Unlike beds of Facies 9 in which cross-bedding delimits the upper part of a depositional continuum, Facies 10 crossbedding is not genetically related to the underlying bed. All beds form sharp erosive contacts with the underlying bed.

Beds comprised of several stacked dunes consist of medium to granule-size sandstone. Single trough cross-bedded form-sets consist of coarser-grained sediment. Often within these form-sets pebble to granule-size clasts delimit the base of well-defined internal laminae which fine upward within the laminae to medium or coarse-grain sandstone. Dunes are bedforms developing in the upper part of the lower flow regime (Simons, *et al.*, 1965). Flow velocities for the development of dunes composed of

medium sandstone to fine-pebble clasts, range from approximately 55 cm/s to greater than 100 cm/s. High flow velocity necessary for depositing coarse-grained beds are probably associated with turbidity currents. Tractional transport of sediment within the "body" or the "tail" of the current is believed to deposit the coarse-grained, single trough cross-bed form-sets found at Redoubt Mountain. Lower velocity flows depositing the finer-grained, stacked dunes at Bath Creek Quarry are interpreted as reworked bed-top features. Reworking is a result of storm currents which have been funnelled through a submarine channel. By channellizing the flow greater velocities and therefore flow competence can be attained.

Within submarine canyons several authors have measured the velocity of "normal" bottom currents (Shephard and Marshall, 1973, 1978; Inman, *et al.*, 1976; Keller and Shephard, 1978). Both up- and down-canyon flows have been measured and are believed to be related to surficial tidal and wave activity. Occassionally these "normal" currents are interrupted by high velocity flows. Some are related to large-scale turbidity currents (Shephard and Marshall, 1978), but others are correlated with smaller-scale events associated with river flood stage and/or intense surficial storms (Shephard, *et al.*, 1977; Keller and Shephard, 1978; Hotchkiss and Wunsch, 1979). Analogous to the presence of sedimentary structures in modern submarine canyons (Bouma, 1965; Got and Stanley, 1974; Birdsall and Scott, 1975), it is believed that under conditions of prolonged competent current activity (probably associated with storm conditions and/or subaerial flooding) individual dune bedforms of Facies 10 observed at Bath Creek Quarry migrated and subsequently deposited one-above-the-other.

FACIES 11.

Features of Facies 11 are very similar to that described by Johnson (in Reading, 1981) as "linsen-bedding". This type of deposit is developed by the migration of starved ripples and discontinuous sand patches over a muddy substrate. Cessation of coarse-sediment supply, associated with decreasing flow regime, results in the arrest of bedform migration and the reinstatement of normal mud accumulation (draping and

eventually burying the isolated bedforms).

Beds of Facies 11 are characterised by graded, parallel-bedded fine sandstone which underlie and drape isolated trough cross-bedded form-sets (interpreted as the deposits from dune bedforms). Fine-grained, parallel bedded sandstones represent the "normal" sedimentation within this environment (deposition of these beds will be discussed in Facies 12). Episodic events, probably related to surface storms, interrupt fine-grain sedimentation with the erosive influx of coarser-grained sediment. Transport of coarse-grained sediment occurs by the migration of isolated dune bedforms. With the passage of the storm and subsequent decrease in flow competence, fine-grain sedimentation resumes, blanketing and burying the senescent dunes.

FACIES 12.

Drake and Gorsline (1973) discovered the existance of very thick (up to > 200 m), low concentated clouds of suspended fine-grained sediment above the base of Californian submarine canyons. These clouds, which they called "nepheloid layers", contained less than 10 mg^{-3}/l suspended sediment. Cyclic flowing "normal currents" tend to concentrate the near-bottom nepheloid current within the confides of the canyon (Malouta, *et al.*, 1981). Such low density suspension layers are incapable of producing significant density underlows, but were believed to explain the net downcanyon transport of water measured by Shephard and Marshall (1973).

Later work by Stowe and Bowen (1980) proposed the deposition of fine-grained, graded beds from the outer Scotian continental margin, from very thick, dilute (10^{-3}mg/l), low velocity (10 - 20 cm/s) turbidity currents. These flows are analogous to the "nepheloid layer" of Drake and Gorsline (1973), and are presently thought to be significant agents transporting fine-grained sediments into the deep-sea (Stowe and Bowen, 1980; Malouta, *et al.*, 1981). Low velocity downslope surges are attributed to shelfal storm-water build-ups and/or peak river discharge (Shephard, 1979; Stowe and Bowen, 1980; Malouta, *et al.*, 1981). Beds of Facies 12 are actually units comprised of a number of thin, graded beds. Each of these small-scale beds are believed to be deposited by

similar low velocity, dilute turbidity currents.

III. CHAPTER 3

A. PALEOCURRENT INFORMATION

INTRODUCTION

This chapter summarizes paleocurrent data collected from both field and laboratory studies. Paleoflow measurements were derived from:

(i) exposed ripple cross-beds from Facies 7 beds
(ii) trough cross-beds from Facies 10 and 11 beds
(iii) flute marks and other linear scour features beneath beds of Facies 7
(iv) pebble imbrication from coarse-grained beds of Facies 2,3,5 and 8
(v) grain imbrication of medium and coarse-grained sandstones (taken from the upper graded parts of Facies 3,4,5, and 6 beds).

Ripple cross-bedding is relatively common in thinly-bedded, fine-grained Facies 7 beds. Paleoflow directions were obtained by measuring the orientation of the maximum dipping plane of ripple cross-stratification. Trough cross-bedding on the other hand is much less common and much harder to measure. Reliable paleocurrent trends can only be ascertained when both trough limbs are exposed. In this rare instance, the precise linear orientation of the trough axis can be determined.

Flute marks and other linear scour marks, indicative of basal scouring, are generally associated with subaqueous turbidity currents. Although rare in this study, these features are observed on the soles of Facies 7 beds. Paleoflow directions derived from these features are usually bipolar. However, in the case of well-developed flute marks, a distinction can be made between the upstream and downstream ends of the scour. This enables the measuring of a unidirectional paleocurrent trend.

Paleoflow data collected from the various sedimentary features described above are listed in Tables 4 and 5 of Appendix III.

Pebble imbrication studies were performed on very coarse-grained beds of Facies 2,3,5 and 8. In these beds, the trend of the maximum dipping "ab" plane of 100 pebbles

per bed were measured. This procedure follows that of Walker (1977). Only those pebbles showing distinct scalar differences in their three principal pebble axis were used. In particular, those pebbles showing a minimum long-axis (a-axis) : intermediate-axis (b-axis) ratio of 1.5:1 were measured. Pebbles were then reoriented about regional bedding and plotted on smoothed rose diagrams, using a program provided by Dr. H.A.K. Charlesworth (Appendix II(ii): Figures 50(a) to 50(j)). This program makes use of a "smoothing parameter", a variable calculated from a von Meises distribution (circular distribution). This variable, denoted "k" quantifies the degree of variance within a series of repeated measurements. For this study five pebbles were selected and repetitively measured ten times. A value of k=377 was computed and used in the smoothed diagram program.

The corrected pebble trends of each data set (those reoriented about bedding), were then analyzed using a statistical method outlined by Curray (1956). This two-dimensional vector analysis makes use of the trend of a line. In this case, the trend of the line is assumed to be equivalent to the maximum dip-direction of the pebble imbrication "ab" plane. Using this method, a two-dimensional vector mean is calculated for each data set. Each vector mean represents the preferred dip-direction of the pebble imbrication plane. With rare exceptions, the "ab" imbrication planes are parallel to, or at small angles to, the orientation of the pebble long-axes (a-axes). A Rayleigh significance test, with a minimum significance level of 95%, was used to determine the reliability of each calculated vector mean.

Acetate peels allowed the acquisition of paleocurrent information from medium and coarse-grained sandstones (see Appendix II(i) for discussion of peel procedure). In this study 100 grains were measured per peel (one peel per bed). Computer plots of moving average rose diagrams, with an interval of 5°, were generated for each data set (Appendix II(ii): Figures 51(a) to 51(m)). The orientation of the preferred grain long-axis within each data set, was determined by calculating eigenvalues (program provided by Dr. H.A.K. Charlesworth). A minimum eigenvalue of 0.65 was set as the basement significance level for testing the reliability of the calculated preferred long-axis attitude.

The eigenvalue method differs from the vectorial method, because it defines a three-dimensional attitude of the preferred long-axis direction, while the vectorial method

delineates the two-dimensional trend of the preferred long-axis direction. However, in both of these methods a point of caution should be emphasized. Application of either of these methods is valid only when the data are distributed in unimodal fashion. Polymodal, and particularly bimodal distributions render erroneous preferred trends or attitudes. To ensure that unimodal distributions were present, the data was first plotted as histograms or rose diagrams. These plots show the distributions and allow the quick determination of the degree of dispersion within the data sets.

BATH CREEK QUARRY.

At Bath Creek Quarry beds are typically graded and structureless. Therefore, field paleocurrent data were collected from the rarely well-exposed tractional structures exhibited in beds of Facies 7, 10 and 11 (Appendix III(i): Table 4). Throughout the measured sections paleocurents show a pervasive SOUTHEAST direction of transport (Figure 43). In rare cases, particularly in fine-grained Facies 7 beds, a NORTHWEST paleoflow direction is observed. These directions are 180^0 from the dominately southeast direction measured in the coarser-grained beds. The northwest direction is believed to represent normal "up-canyon" current surges reported in modern submarine canyons by Inman, *et al.*, 1976; Shephard and Marshall, 1978; Keller and Shephard, 1978.

REDOUBT MOUNTAIN.

At this study location because of the scant occurrence of well-exposed tractional structures, acetate peels and clast imbrication studies were included to bolster the paleocurrent data base.

Field Data:

Unlike the situation at the Bath Creek Quarry, paleocurrents from Redoubt Mountain are more widely dispersed (Appendix III(ii): Table 5). However, individual measurements can be clustered into three main groups, each directly related to the outcrop position of the bed(s) characterizing that group. Paleoflows derived from beds in

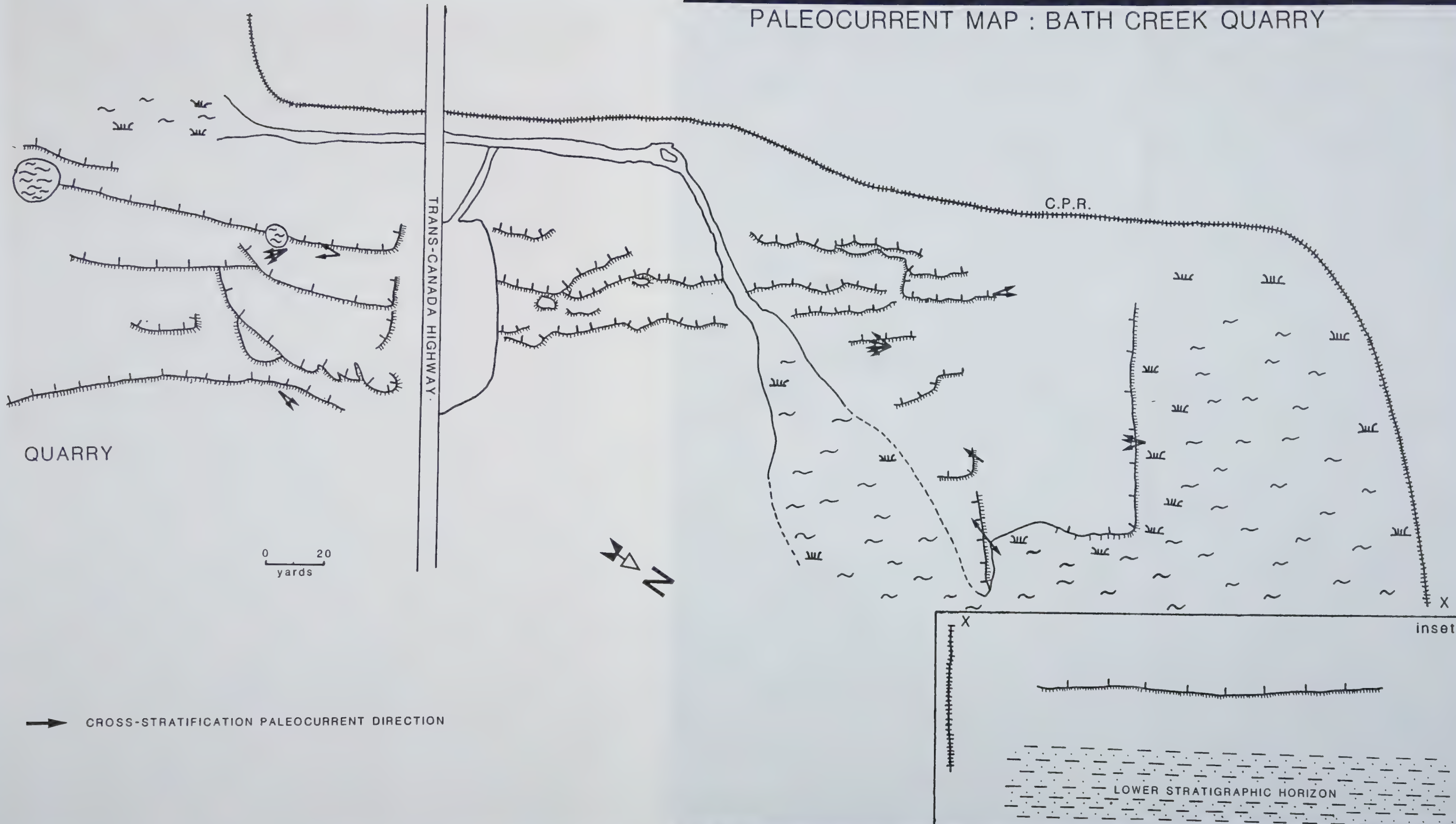

PALEOCURRENT MAP : BATH CREEK QUARRY
C.P.R.
TRANS-CANADA HIGHWAY
QUARRY
0 20
yards
N
X
X
inset
LOWER STRATIGRAPHIC HORIZON
CROSS-STRATIFICATION PALEOCURRENT DIRECTION

FIGURE 43.

sections furthest removed from the channel wall (Section 3,4 and 5) show a pervasive NORTHEAST direction of transport (Figure 44). With increasing proximity to the channel wall there is a similar increase in paleocurrents trending in a NORTHWEST direction (Figure 44). Northwest and particularly northeast paleocurrent directions appear to contradict the southwest to westward paleoflows reported in coarse-grained Miette clastics by Mountjoy and Aitken (1963). These seemingly anomalous directions may have paleoenvironmental implications and will be discussed in greater detail in Chapter 4. Capping the coarse clastic beds at both study areas is a thick interbedded package of thinly-bedded Facies 7 turbidites and slates (the Upper Slates of Aitken, 1969). Paleocurrents from this upper stratigraphic horizon show a distinct SOUTHWEST to NORTHWEST direction of transport.

Acetate Peels:

Unfortunately most of the beds encountered in this study are typically structureless, making the preparation of acetate peels essential for determining sediment dispersal patterns. A summary of the acetate peel paleoflow data is summarized in Figure 44; Appendix II(ii): Figures 51 (a) through (m) and Appendix II(iii): Table 4.

Paleoflow directions derived from Facies 5,6,7 and 12 beds show a dominantly NORTHEAST with less common NORTHWEST direction of transport. Anomalous paleocurrent directions derived from Facies 2,3 and 4 beds may have paleogeographic significance, but because of the possible cyclic turnover of debris flow fabric during flow, those results may not be reliable.

Field Imbrication:

As expected beds of Facies 2 and 3 (Appendix I(i): Figure 50(d), (f),(g)). show a great diversity in imbrication direction. However, beds of Facies 5 and 8 typically show a more clustered distribution of imbrication directions, and in the case of: (i) Bed 21, Section 1 (Facies 8); (ii) Bed 57, Section 4 (Facies 8); (iii) Bed 64, Section 5 (Facies 8) and (iv) Bed 151, Section 6 (Facies 8) (Appendix I(i): Figure 50 (a),(b),(c),(i); Appendix I(ii): Table 2), show a moderately well-defined southwest imbrication associated with a NORTHEAST direction of transport. Bed 163 Unit A, Section 7 (Facies 5) (Appendix I(i): Figure 50(i);

PALEOCURRENT MAP : REDOUBT MOUNTAIN

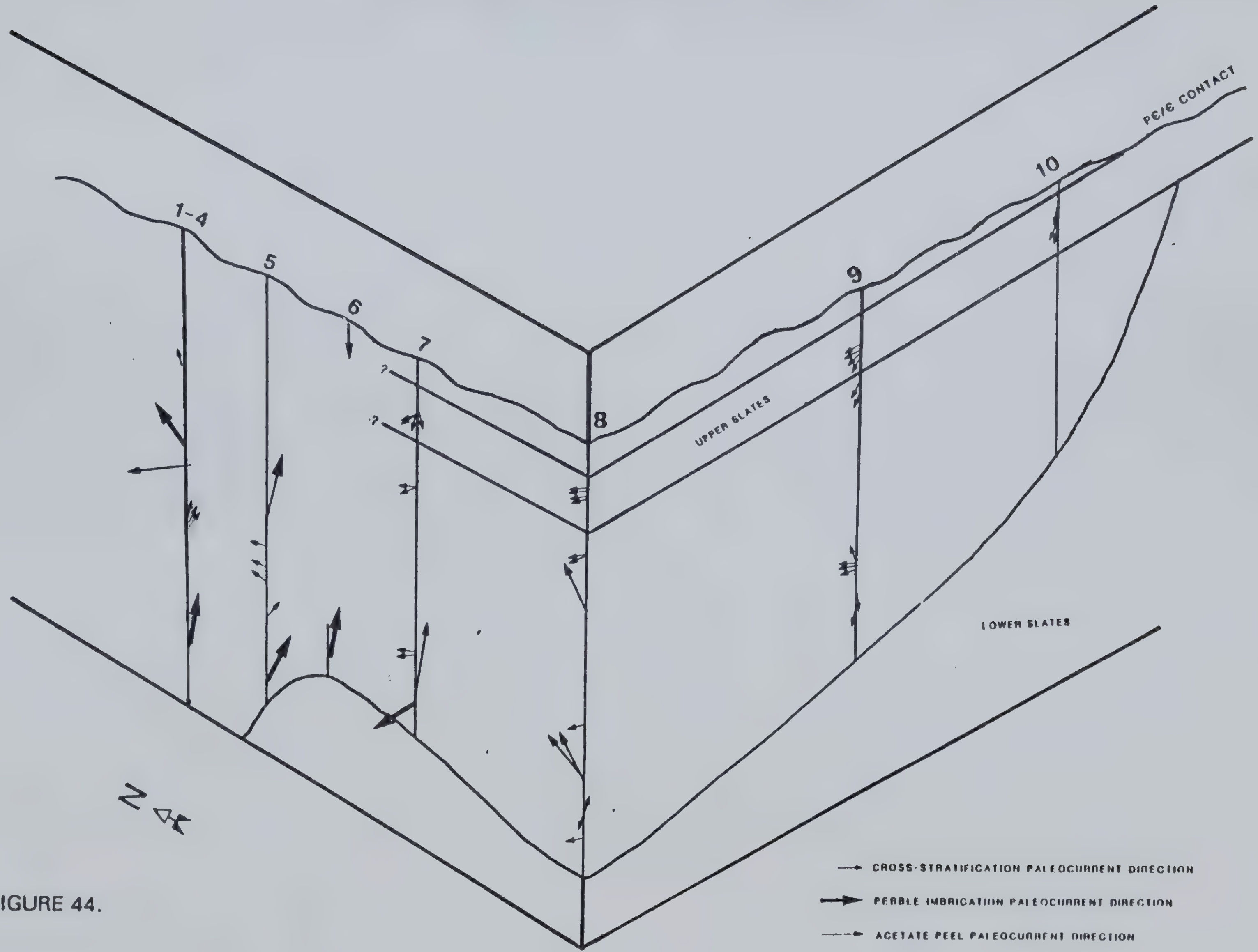


FIGURE 44.

Appendix I(ii): Table 2) on the other hand indicates a <u>WESTWARD</u> paleoflow.

IV. CHAPTER 4

Deep-marine lithologies of the Upper Precambrian Hector Formation near the town of Lake Louise, Alberta consist of a thick package of typically coarse-grained sediment-gravity flow deposits. At both Bath Creek Quarry and Redoubt Mountain a horizon of thinly-bedded Facies 7 turbidites, interbedded with grey-black slates (the Lower Slates of Aitken (1969)), forms a natural stratigraphic boundary in this study. On the west and south faces of Redoubt Mountain, coarse clastic sediment forms a large-scale channel-fill complex, erosively cut into the strata of the Lower Slates (Appendix VI). The fill is composed of eight vertically fining- and thinning-upward sequences (channel-filling events), which together comprise a multistorey fining- and thinning-upward cycle (Figure 45). Similarily, at Bath Creek Quarry, a number of upward-fining and -thinning sequences characterise the channel-fill (Figure 46), but due to the poor nature of the outcrop cannot be traced laterally for any great distance.

Beds comprising the Lower Slate horizon show typical features of fine-grained continental slope deposits (Stanley, 1975). Large submarine channels or submarine canyons often incise thinly-bedded, fine-grained continental slope strata, particularly off-shore of large fluvial systems. Ancient examples of submarine canyons are relatively rare in the geologic record, a consequence of the tectonic instability of the continental slope.

A. FACIES ASSOCIATIONS:

Three main associations can be recognized in the Hector Formation. These are described and interpreted below and summarized in Table 1.

FINE-GRAINED ASSOCIATION.

This association is restricted in outcrop to the two stratigraphic marker horizons referred to in the preceding text as the "upper" and "lower" slates. These are characterised by fine-grained, thinly-interbedded strata of Facies 7 turbidites and grey-black slate.

SEQUENTIAL CHANNEL FILL EVENTS - REDOUBT MOUNTAIN

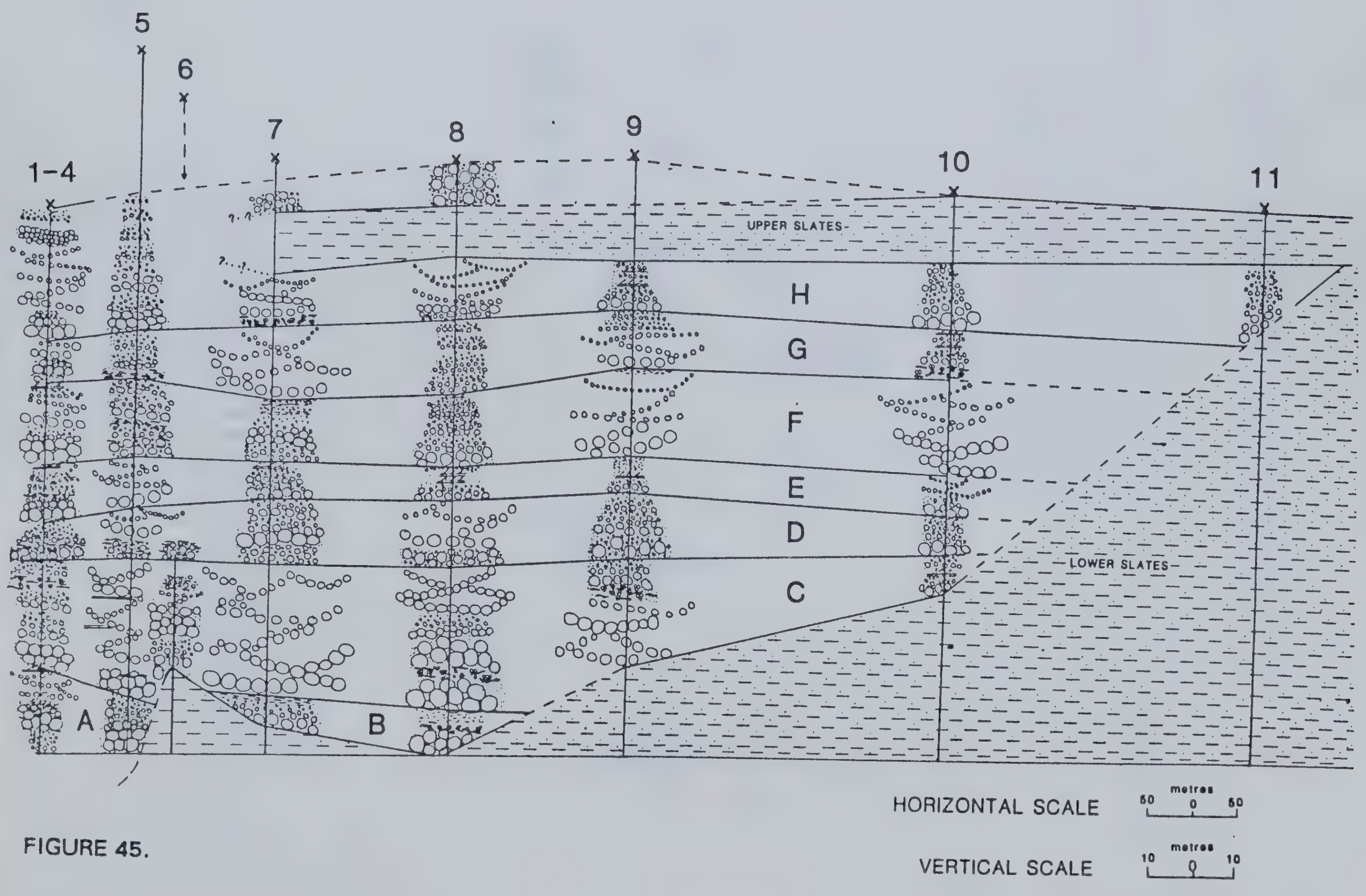


FIGURE 45.

CHANNEL FILLING EVENTS - BATH CREEK QUARRY

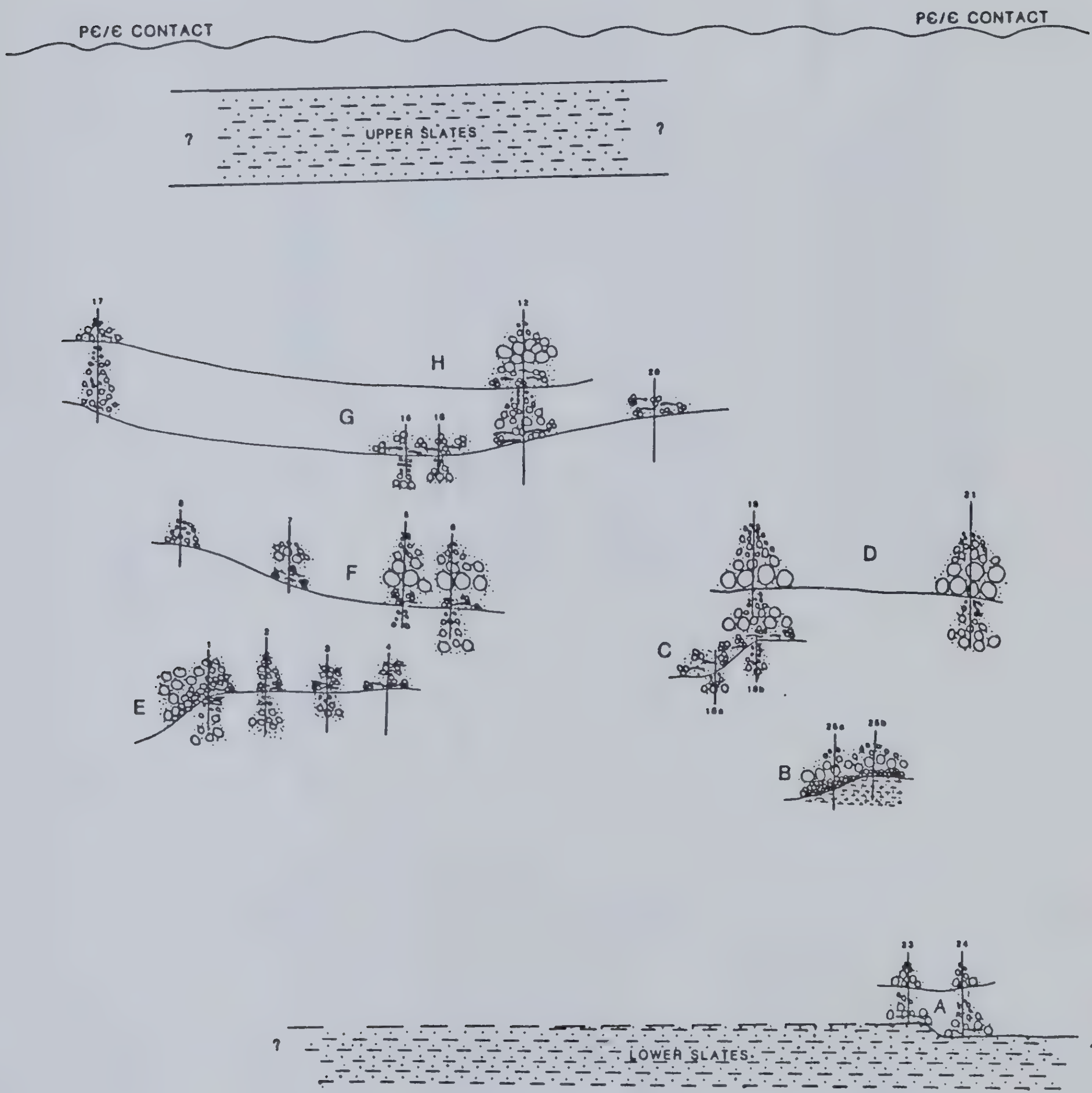


FIGURE 46.

TABLE 1

ASSOCIATION NAME	MAJOR LITHOFACIES	MINOR LITHOFACIES	DEPOSITIONAL INTERPRETATION
COARSE-GRAINED ASSOCIATION	1,2,3,5	8,9	Forms the basal portion of each channel-filling event within each canyon-fill. Domination of large-scale mass movement and sediment-gravity flow processes.
MEDIUM-GRAINED ASSOCIATION	4,6,7	8,10,11,12	Comprises the upper region of each channel-filling event within the canyon-fill. Typically smaller-scale, often well-stratified sediment-gravity flow processes.
FINE-GRAINED ASSOCIATION	7,ss,sl	---	Comprises the upper and lower slates. Interpreted as typical fine-grained continental slope deposits. These beds are sedimented from hemipelagic fall-out plus nepheloid and very small-scale, fine-grained turbidity current flows.

Turbidites typically only show upper Bouma BCD and CD divisions. Beds of this nature indicate sedimentation within a quiet, depositionally "distal" environment. Slate beds on the other hand, represent fine-grained hemipelagic fall-out, and/or deposition from nepheloid flows. Lithologies of this description are similar to typical fine-grained continental slope sediments.

At both Bath Creek Quarry and Redoubt Mountain, the Lower Slate horizon is deeply incised by a large-scale submarine channel. Coarse clastic sediment representing the channel-fill, abruptly pinch-out against the lower slates which bound the fill on three sides. The co-existance of the Fine-Grained and Coarser-Grained Associations are not uncommon in both ancient and modern continental slope environments, and represent the filling of a deactivated submarine canyon.

At both study locations, the Upper Slates form a conformable cap covering the filled canyons. Turbidite beds, with minor interbeds of slate, dominate the lower region of the upper slates, but this trend reverses with increasing stratigraphic height. This upward reduction in the percentage of the coarse-grained tubidites is probably related to decreasing regional controls on sediment supply to the basin (*e.g.* progressing marine transgression).

COARSE-GRAINED ASSOCIATION.

This association is characterised by thick, coarse-grained beds of Facies 1,2,3,5 and 8. At both study locations, this sequence dominates in the lower area of each channel-filling event, particularly in the lower two-thirds of the channel-fill. The occurrence of these beds represents a period of intense sediment instability and widespread mass movement and sediment-gravity flow activity. This may be in reponse to periodic increases in sediment influx and grain size, related to local tectonic and/or sedimentary controls (probably a combination of the two). Local tectonic effects probably reflect small-scale seismic disturbances either within the depositional basin or in the immediate sediment source area (*e.g.* earthquakes). Local sedimentary controls may include processes such as deltaic shifting, channel avulsion *etc.*.

Graded debris flow deposits are volumetrically the most abundant in this sequence, suggesting a period of intense sediment instability in the immediate sediment source area. Less abundant, graded and ungraded dispersion deposits, associated with large-scale turbidity currents are indicative of the energetic nature of this facies association. Most beds show scoured, or less commonly, channelled basal contacts.

MEDIUM-GRAINED ASSOCIATION.

This sequence is dominated by thinner, finer-grained deposits than those characterising the Coarse-Grained Association. Moderately erosive to non-erosive flows depositing the beds of Facies 4,6,7 and less commonly 9,10,11 and 12 characterise this sequence. Debris flow deposits are still volumetrically the most abundant, but stratified facies comprise a much larger portion of this association. Beds of the Medium-Grained Association lie stratigraphically above and lateral to beds of the Coarse-Grained Association. Those lying above, comprise the upper part of each channel-filling event, forming a transitional contact with the underlying beds of the Coarse-Grained Association. This upward reduction in coarse-grained sediment supply is probably related to the diminution of local sedimentary and/or tectonic effects on basin sedimentation. Those beds grading laterally into beds of the Coarse-Grained Association, reflect the progressive reduction in flow regime and therefore competence within a channellized sediment-gravity flow.

The top of this association is identified by the abrupt, erosive recurrence of the Coarse-Grained Association.

B. CHANNEL MODEL

In modern deep-sea environments, coarse-grained sediments are typically restricted to submarine fan and continental slope channels, but have been observed in abyssal plain channels (Chough and Hesse, 1976). The observation of the

deeply-channellized package of beds comprising the Coarse and Medium-Grained Associations within strata of the Fine-Grained Association at both study locations, is believed to represent the filling of two such deep-sea channels. The lack of levee deposits, the virtual lack of cross-bedding and the abundance of debris flow deposits imply that these two channels represent continental slope, and / or shelf-break submarine canyons.

Reports of ancient submarine canyons are rare in the literature, particularly in the Precambrian. Incision of a submarine canyon usually coincides with a eustatic low-stand when fluvial systems are able to traverse the continental shelf and deliver their load directly to the slope. With the predominance of narrow continental shelfs during the Precambrian, sea-level changes may not necessarily have been large in order for fluvial systems to bridge the shelf. Subsequent sea-level rise and an associated marine transgression could then result in the sediment starvation of the slope with the gradual deactivation of the canyon(s). Continued trangression results in the aggradation and eventual onlap of the submarine fan facies, which, if given sufficient time, could back-fill the canyon (von der Borch, *et al.*, 1982). The overall sedimentary package representing the canyon-fill would therefore be characterised by an overall fining- and thinning-upward mega-cycle.

Sedimentary process effects need not be the only processes altering time-related sedimentation style. The gradual diminution of regional tectonic uplift in the sediment source area, and / or the reduction or cessation of basin subsidence, could produce a similar fining- and thinning-upward mega-cycle. Tectonically controlled sedimentary patterns, similar to those just described, have been reported in other deep-sea basins by: Cossey and Ehrlich, 1978; Almgren, 1978; Surlyk, 1978; Martini, *et al.*, 1978; von der Borch, *et al.*, 1982; Hurst and Surlyk, 1983.

At Redoubt Mountain, a minimum 135 metre fining- and thinning-upward channel-fill can be observed. At the Bath Creek Quarry, a channel-fill of similar attributes can be identified, but due to the structural complexity of the area an accurate estimate of total thickness could not be ascertained. Channel-fills of this description indicate that, as a function of time, sedimentation within the respective canyons is becoming progressively more "distal" in nature. This implies a long-term sedimentological control on coarse clastic

sedimentation within the basin. This may be the result of a continually progressing transgression occurring throughout deposition of the Hector Formation. However, as previously mentioned, the diminution of regional tectonic activity could also reduce coarse clastic supply to the basin, but unfortunately would be difficult to differentiate from strictly sedimentary process effects.

Within the large-scale channel-filling cycles at Redoubt Mountain and Bath Creek Quarry, a number of small-scale fining- and thinning-upward sequences are observed. Coarse, thickly-bedded strata of the Coarse-Grained Association characterises the lower portion of each sequence. The abrupt and recurring influx of this association above finer / thinner deposits of the Medium-Grained Association indicates a relatively short-lived, episodic event which abruptly changed the sedimentary style within the basin. These events are probably under relatively small-scale, local sedimentary and / or tectonic control.

Capping the canyon fills at both study locations are beds characterising the Fine-Grained Association. These beds represent the return of very fine-grained sedimentation within the basin, indicating the maximum extent of marine transgression during deposition of the Hector Formation.

The channel-fills at Bath Creek Quarry and Redoubt Mountain are dominated by debris flow deposits. Debris flows are viscous sediment-gravity flows which characterise the early stages of a sediment-gravity flow continuum (Morgenstern, 1967; Middleton and Hampton, 1973, 1976; Walker, 1978; Lowe, 1982). With increasing distance of travel, these flows can be modified by liquefaction and remolded into other mass-gravity flows in which matrix strength is no longer the primary sediment supporting mechanism. Debris flow deposits are typically restricted to "proximal" depositional environments (Walker, 1975a, 1977, 1981; Lowe, 1982), while the deposits of the more "fluid" flows (*e.g.* turbidity currents, liquified flows) dominate more "distal" lithologies. Debris flows are probably the product of liquifed slump / slide deposits that originated on or near the canyon wall. This process has been reported in modern canyon complexes, where debris flow deposits lying in the axis of the canyon represent liquified slump beds which have moved down and away from the canyon wall (Stanley, 1974). Erosive basal contacts of debris flow deposits characterise beds of Facies 2 and 3, and are indicative of debris

flow in steep slope environments (Pierson, 1980). On the continental slope such environments are restricted to submarine canyon walls. Normal, with less abundant inverse and inverse-to-normal grading characterise the debris flow deposits in both study areas. This contrasts the typically ungraded debris flow deposits reported in many other coarse-grained submarine canyon fills (Stanley and Unrug, 1972; Stanley, 1975; Walker, 1975a, 1977; Cossey and Ehrlich, 1978). This difference may be a consequence of the rapid resedimentation of poorly consolidated debris at Bath Creek Quarry and Redoubt Mountains. Consequently, these flows are more "fluid", enabling a higher degree of internal clast mobility within the flowing debris. Liquefaction of debris flows, with the development of significant fluid turbulence and dispersive pressure, probably results in the destruction of viscous dominated flow and the development of clast dispersion flows that deposited beds of Facies 5 and 6.

Deposition from channellized debris flow and dispersion flow results in the development of the "multi-scour" facies (Figures 47 and 48). This feature is characterized by a thick package of superimposed channel-fills, and appears analogous to the "nested" channel sequences reported in actively migrating and aggrading channel areas in both ancient (Mutti and Ricci Lucchi, 1978; Walker, 1975b) and modern (Normark and Piper, 1982) deep-sea environments. The coarsest-grained sediment present at any particular stratigraphic level usually occurs within this facies, passing laterally into finer-grained, better-stratified, unchannellized deposits.

Several features differentiate the deposits at the two study areas. Beds at Bath Creek Quarry are generally finer-grained and thinner-bedded than those at Redoubt Mountain. This indicates the prevalence of smaller, less competent sediment-gravity flows depositing the beds at the Bath Creek Quarry. Beds of Facies 1 (slumps and slides) are more abundant at the Bath Creek Quarry. This may be a consequence of decreased relief within the canyon at the Bath Creek Quarry study area. In an environment such as this, slumps and slides are less susceptible to liquefaction effects because of shorter travel distance. Conversely, greater relief of the canyon at Redoubt Mountain results in the remolding of slumps and slides into various other types of sediment-gravity flow.

One of the most striking differences between the two study areas is the absence of both Facies 10 and 11 beds at Redoubt Mountain. These facies are commonly found in

FIGURE 48: Small-Scale Multi-Scour Facies.

FIGURE 47: Large-Scale Multi-Scour Facies.

continental shelf environments, where sufficiently competent currents transport and deposit sand-sized sediment in large dune bedforms. As a result, their absence at Redoubt Mountain may imply a deeper depositional environment than that inferred for the Bath Creek Quarry area. However, these facies are particularly abundant in the upper regions of the canyon-fill at the Bath Creek Quarry. This may imply a depositional shoaling of the Bath Creek Quarry canyon into depths where shallower-marine currents are of greater influence.

Paleocurrent trends are also markedly different between the two study areas. Those at Bath Creek Quarry show a dominately southeast direction, whereas northeast and northwest directions are indicated at Redoubt Mountain. The southeast and northeast paleoflows represent the downcanyon trend of the respective canyons. The seemingly anomalous northwest directions at Redoubt Mountain are of greater abundance near the canyon wall. This direction represents flows which moved down the wall and were immediately deposited on the "proximal" canyon floor (with respect to the canyon wall). This feature can be used to infer relative positioning of measured sections within an ancient submarine canyon-fill, when the channel wall is not visible (such is the case at Bath Creek Quarry).

Most studies of ancient submarine canyon-fills make use of the classic facies reconstruction of an Uppermost Eocene to Lower Oligocene submarine canyon complex by Stanley (1975). In his model, Stanley identifies a number a sedimentary features which are characteristic of a particular depositional area within the canyon. These facies can be used as a framework for similar deep-sea channel studies. Presented below is a short review of Stanley's sedimentary facies encountered in a coarse-grained canyon-fill and their geographic significance.

CANYON FILL FACIES.

This facies is characterised by a thick, wedge-shaped, concave-up package of coarse-grained, massive units possessing a very high sand:shale ratio. Successive beds show a typically exhibit a lack of uniformity and erosive basal features. Thin discontinuous shale beds, and/or a horizon of shale rip-up clasts within coarser-grained beds, attest to the erosive nature of the flows depositing these beds.

Beds are commonly graded, showing both inverse and normal types, and in some cases have an "a-axis" upstream clast imbrication. Tractional sedimentation features are rarely observed, although some finer-grained beds do show some stratification. Within the canyon-fill, paleoflow patterns have a low dispersion or variance and point to a pervasive downslope transport direction. Slump blocks and debris flow deposits are common. Both upper Bouma division turbidites and shale beds rarely occur.

CANYON WALL FACIES.

This facies is laterally equivalent to the Canyon Fill Facies. It differs by having a well-developed stratification and reduced sand:shale ratio. Slump, debris flow and grain flow deposits are also proportionally higher.

Paleoflow directions are seemingly anomolous and vary up to 90° from those observed in the Canyon Fill Facies. These divergent paleoflows reflect local transport down the walls and out onto the canyon floor, in a direction perpendicular to the regional downslope trend.

TRIBUTARY CANYON FACIES.

This facies can only be accurately identified when the main Canyon Fill Facies has been located. Tributary Canyon Facies are thinner-bedded, finer-grained and better-stratified than those of the Canyon Fill Facies. Paleoflow patterns are divergent from those in the Canyon Fill Facies. Identification of the Tributary Canyon Facies relies on paleogeographic reconstructions in relation to the main Canyon Fill Facies.

INTERCANYON FACIES.

This facies contrasts markedly with those already discussed. Thin, well-stratified fine sandstones and siltstones as well as an enhanced proportion of shales characterise this facies. Turbidites show BCDE or CDE Bouma sequences and have paleoflow patterns consistent with paleoflows of the main Canyon Fill Facies. Trace fossil densities and diversity are much higher than the other facies. This suggests a lower energy environment, more suitable to the life habits of benthic organisms (this last feature does not apply to the non-fossiliferous Upper Precambrian Hector Formation).

C. PRECAMBRIAN PALEOGEOGRAPHY

The uppermost Precambrian (Hadrynian) Hector Formation near the town of Lake Louise, Alberta represents an ancient continental slope. Beds of the Fine-Grained Association comprise the Lower Slate horizon, used in this study as the lower stratigraphic marker. Beds of this association are characteristic of the typically fine-grained sedimentation observed on modern continental slopes. Cut into the Lower Slates at both Bath Creek Quarry and Redoubt Mountain are two large-scale submarine channels, which because of their association with continental slope deposits are referred to as submarine canyons. These canyons may have been cut during a period when rivers were able to traverse the continental shelf and deposit directly onto the continental slope. With an ensuing marine transgression, progradation and eventual onlap of the submarine fan facies back-filled the deactivated slope canyons.

Intense rifting is believed to dominate Upper Precambrian time in the Southern Canadian Rocky Mountains. This has been proposed to represent the predecessor of a continental break-up, which in this area is believed to have occurred in latest Precambrian or earliest Cambrian time (Bond and Kominz, 1984). The Hector Formation therefore, represents a syn-rift depositional suite of continental slope sediments deposited prior to continental separation. This suggestion correlates well with a number of similar aged, syn-rift submarine canyon-fills reported in the Adelaidian Rift Belt of South Australia (von der Borch, 1980; von der Borch, *et al.*, 1982). In both the Canadian and Australian examples, the break-up unconformity is believed to represent the Precambrian / Cambrian contact, which in the Lake Louise area is illustrated by the unconformable Hector / Gog contact (used in this study as the upper stratigraphic boundary). This unconformity may represent the removal of an indeterminant amount of Upper Precambrian strata deposited after the Hector Formation. Unfortunately, due to the limited regional scale of this thesis and the sparseness of earlier studies in this area, an estimate of the amount of strata removed by the unconformity cannot be made.

The coarse-grained canyon-fills at both Bath Creek Quarry and Redoubt Mountain can be subdivided into a number of small-scale (15 - 20 metres) thinning- and fining-upward sequences. These sequences are probably the result of localized, relatively short-lived and recurring sedimentary and / or tectonic events. The abrupt and erosive

influx of the Coarse-Grained Association marks the base of each sequence (channel-filling event). This then grades upward and laterally into thinner, finer-grained beds of the Medium-Grained Association. Together, the small-scale sequences define a mega upward-fining and -thinning cycle which may be a product of regional tectonic (uplift and / or basin subsidence), and / or sedimentary (prograding marine transgression) controls.

Coarse clastic channel-filling deposits at the Bath Creek Quarry consist of finer-grained, thinner-bedded sediment-gravity flow deposits when compared to similar beds at Redoubt Mountain. Slump and debris flow deposits dominate the lithologies, constituting a depositional assemblage correlative with the "Tributary Canyon Facies" of Stanley (1975). Together with the combined occurrence of sedimentary features described by Facies 10 and 11, it is believed that this area represents a relatively shallow depositional environment. Bath Creek Quarry is therefore interpreted as a relatively shallow Tributary Canyon-Fill (Figure 49). Canyons of this description act as conduits, funnelling sediment from the continental shelf-break and / or upper continental slope environment into the upper reaches (head) of the main canyon system. Paleocurrents at Bath Creek Quarry show a distinct southeast direction of transport, marking out the down-axis trend of the canyon. The parallelism of paleocurrent directions reported from various beds throughout the measured sections may indicate a relatively axial position within the canyon-fill. In this region of the canyon, lateral influence of undiverted flows moving into the canyon directly from the walls are minimized.

Coarse clastic sediment-gravity flow deposits at Redoubt Mountain comprise a multistorey fining- and thinning-upward canyon-fill. The typically more erosive basal contacts, thicker beds, and coarser-grain size indicate more energetic, competent flows transporting and depositing beds in this area than those indicative of the canyon-fill at the Bath Creek Quarry. Combined with the absence of shallow water sedimentary facies (Facies 10 and 11), it is suggested that the canyon reported at Redoubt Mountain represents a deeper area of the continental slope than that implied for the Bath Creek Quarry. Exposure of the canyon wall indicates that the Redoubt Mountain sections represent the Canyon Wall Facies of possibly the Main Canyon-Fill within this area (Figure 49). Paleoflow directions derived from sections furthest removed from the canyon wall, show distinct northeast transport. This direction represents flows which, at the time of

PALEOGEOGRAPHY OF THE HECTOR FORMATION
LAKE LOUISE, ALBERTA

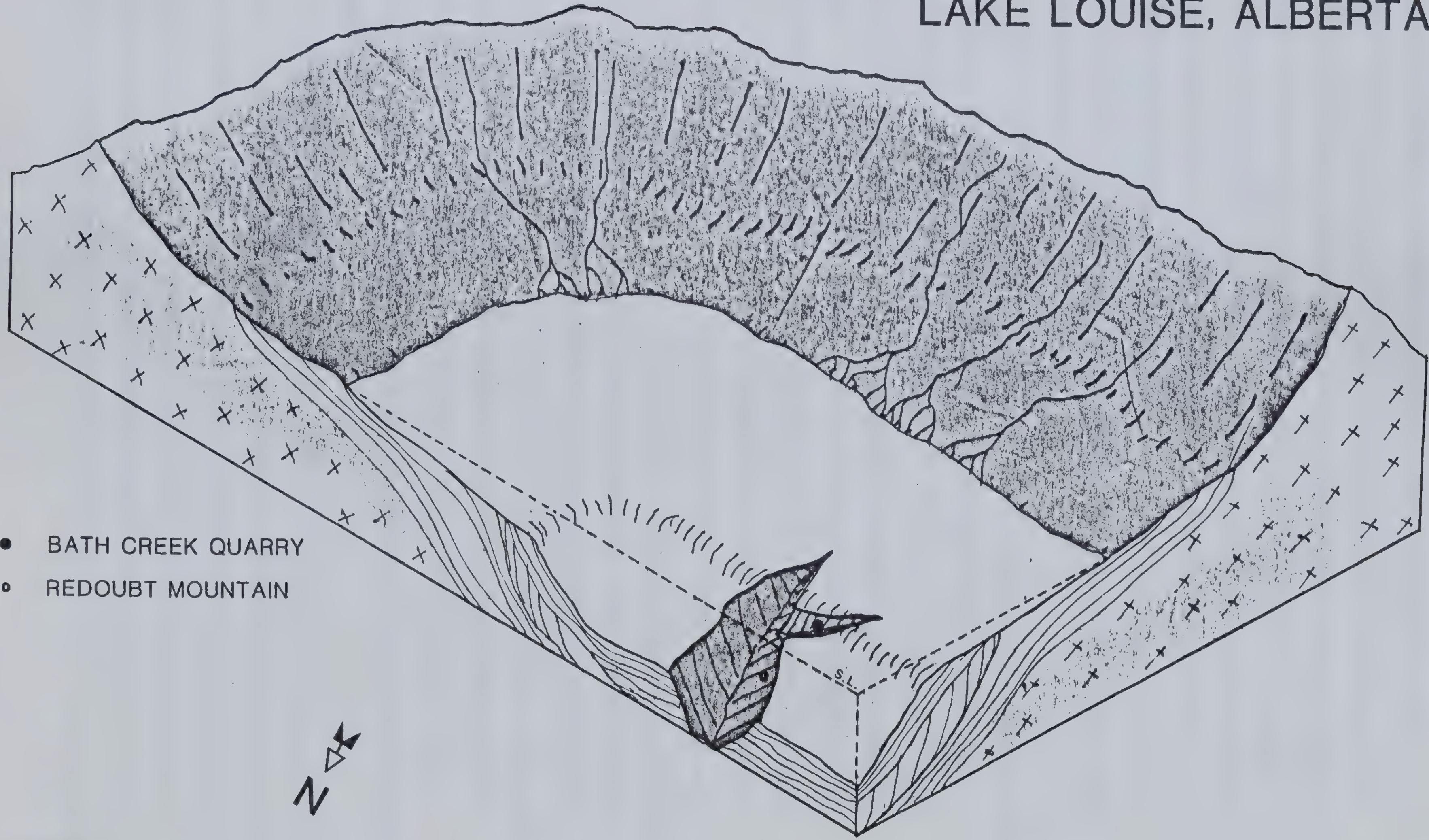


FIGURE 49.

deposition, were moving parallel to the canyon's downslope axis. Anomalous paleocurrents, those typically showing a northwest direction of transport, are most common in beds cropping-out closer to the canyon wall. These directions indicate the influence of flows which, having moved down the canyon wall, were immediately deposited in the "proximal" areas of the canyon floor (the area nearest the wall / floor break). However, flows possessing greater "fluidity" would be less effected by the abrupt decrease in slope at the wall / floor break and would move out onto the canyon floor. Soon after, these flows would be diverted into a downcanyon direction, consequently showing a northeast paleocurrent direction.

Following the filling of the canyon at both study locations, typical continental slope sedimentation resumes. This is indicated by the resumption of fine-grained clastic sedimentation, formulating the Upper Slate horizon. At both Bath Creek Quarry and Redoubt Mountain paleocurrent directions generally trend toward the southwest to northwest. The inference of an easterly lying source terrain (Canadian Shield) for the Upper Slates differs markedly from the southerly source inferred for the underlying canyon fills. A possibile explanation for this seemingly erroneous conclusion is the presence of a large embayment off the western coast of the North American Craton in the area of Hector Formation deposition. The inferred involvement of the craton is verified by the mineralogical similarity of Hector Formation and Canadian Shield rocks (Appendix IV: Table 6 and Table 7). Submarine canyons trending northeast and southeast depict a portion of the craton's continental slope, which at the time of Hector Formation deposition was dipping in a northward direction. Following the filling of the canyons and likewise the embayment, normal sedimentation of fine-grained clastic sediment derived from the easterly lying craton resumed covering the area with a blanket of fine-grained continental slope deposits.

An alternative hypothesis for the Hector Formation channel-fills is that they represent filled submarine canyons that were trending down a slope within an intracratonic rift basin. With the prevalence of intense regional rifting during Hector time, deposition of typically fine-grained sediment (represented by the Lower Slates) was interrupted by a tectonically influenced influx of coarser-grained sediment. This period of large-scale, coarse-grained sediment-gravity flows would be in response to tectonic uplift within the

source area and / or subsidence within the depositional basin. The large-scale fining- and thinning-upward channel-filling cycle, would reflect the reduction of competent depositional flows resulting from both the diminution of regional tectonic activity and the continued filling of the basin. Small-scale fining- and thinning-upward sequences may be the product of local sedimentary and / or local tectonic influences. With an indeterminate amount of basin-fill and consequently canyon-fill, fine grained deposition (represented by the Upper Slates) resumes. Sediments in this upper stratigraphic horizon are derived from a distinctly easterly lying source. Unfortunately this hypothesis can be neither verified nor disproven without further regional studies, and the detailed recontruction of the regional paleogeography.

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VI. APPENDIX I

A. PEBBLE IMBRICATION

(i) Imbrication Plots; Figures: 50(a) through 50(j)

(ii) Table 2: Pebble Imbrication Summary

(i) Imbrication Plots; Figures: 50(a) through 50(j)

Each rose diagram represents 100 measured pebble trends.

(a)

BED 21

SECTION 1

FACIES 8

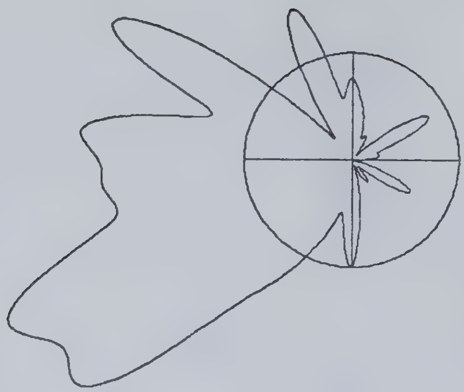
(b)

BED 57

SECTION 4

FACIES 8

(c)

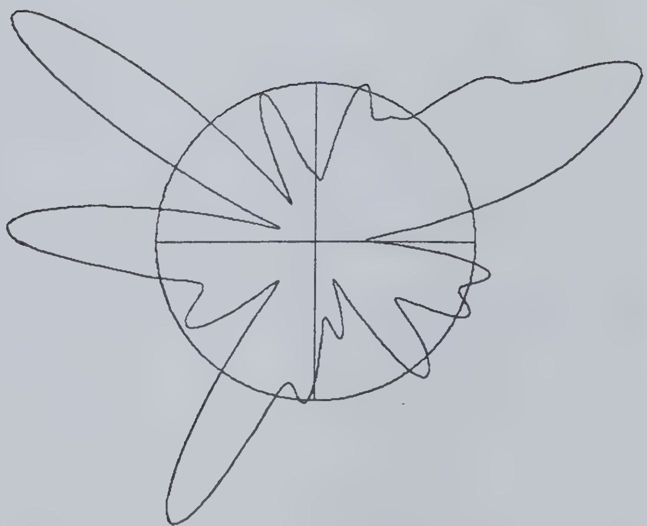


BED 64

SECTION 4

FACIES 8

(d)



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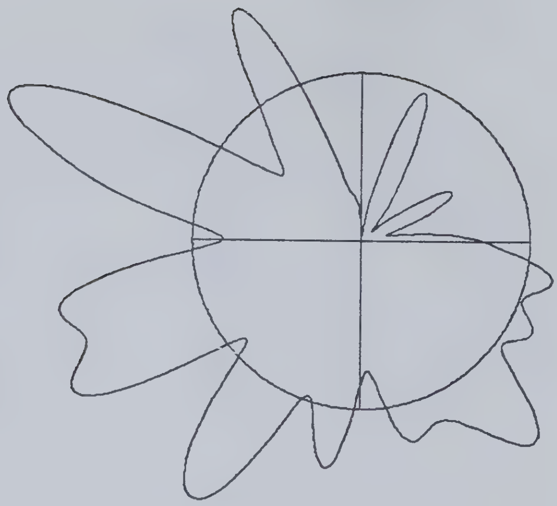
SECTION 4

FACIES 2

(e)



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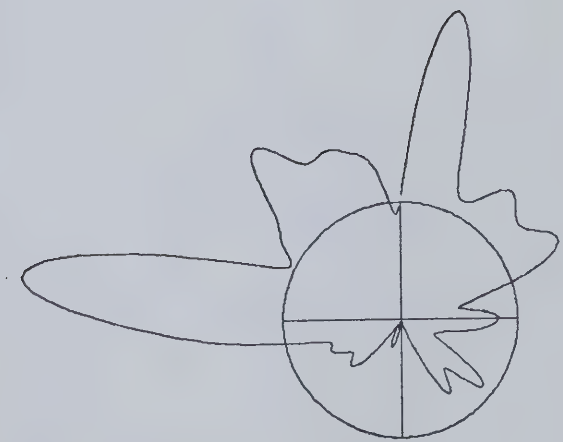
SECTION 4

FACIES 8

(f)



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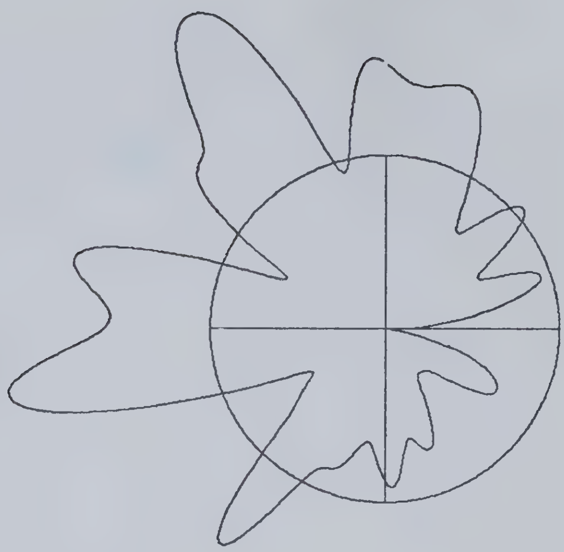
SECTION 4

FACIES 2

(g)



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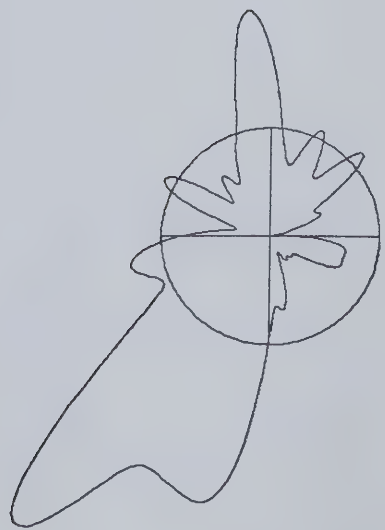
SECTION 5

FACIES 3

(h)

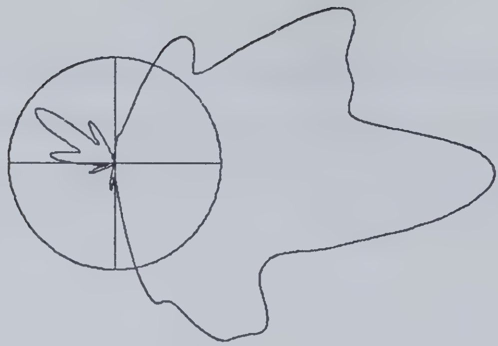


BED 151

SECTION 6

FACIES 8

(i)

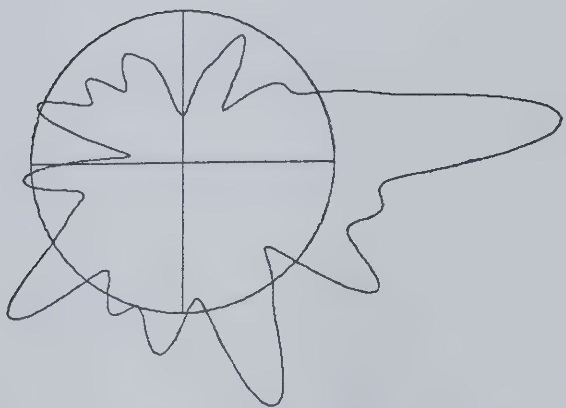


BED 163 A

SECTION 7

FACIES 5

(j)



BED 4

SECTION 8

FACIES 8

(ii) Table 2: Pebble Imbrication Summary

Transport direction is 180° to the Imbrication Vector Mean (I.V.M.) L is the magnitude of the resultant vector in terms of a per cent. In this study a basement significance of 95% has taken which corresponds to an $L > 17.31$, any group with an $L < 17.31$ was disregarded (N.A.).

Table 2

Pebble Imbrication Summary

Figure No.	I.V.M.	L
50(a)	231	26.34
50(b)	204	48.11
50(c)	248	54.54
50(d)	N.A.	N.A.
50(e)	N.A.	N.A.
50(f)	327	41.83
50(g)	N.A.	N.A.
50(h)	230	27.45
50(i)	87	59.23
50(j)	N.A.	N.A.

I.V.M. = Imbrication Vector Mean measured in degrees

L = Vector Magnitude

N.A. = Not Applicable (i.e. L is less than 17.31)

VII. APPENDIX II

A. ACETATE PEEL DATA: REDOUBT MOUNTAIN

(i) Paleocurrent Information From Coarse-Grained Structureless Beds - the use of acetate peels

(ii) Acetate Peel Plots; Figures: 51(a) through 51(m)

(iii) Table 3: Summary of Acetate Peel Data

(i) Paleocurrent Imformation From Coarse-Grained Structureless Beds - the use of acetate peels

The main problem interpreting dispersal patterns and the overall paleoflow direction of the coarse-grained sediments encountered in this study, is their typical lack of primary tractional sedimentary structures. This makes the collection of paleocurrent data virtually impossible in the field.

Oriented samples were selected from the finer-grained, upper regions of graded beds or from the "b" divisions of discernible turbidite beds. Strike and dip of the local bedding, plus a reference "north-arrow" were placed on the rock with indelible ink. Slabs were initially cut in the plane-of-bedding. Cut surfaces were polished, etched with hydrofluoric acid and then placed "face-down" in a methylene blue solution. This staining procedure preferentially colours the fine-grained matrix, producing a marked contrast with the unstained coarse clastic grains.

Using the peel as a photographic negative, peels were individually mounted on a photographic enlarger and projected onto a 16" X 12" sheet of plain paper (photographic paper can be substituted in order to obtain a permenant copy). Long-axis trends of 50 clasts (with a long-axis : short-axis ratio of a minimum 1.5: 1) and the trace of the reference "north-arrow" were marked onto the plain paper. Azimuth of each long-axis was calculated with respect to the "north-arrow", and a vector mean (eigenvalue) computed. Unfortunately paleoflow directions by this method can only be determined to within 180° of the true orientation.

Samples showing a strong preferred orientation of their long-axis trends following the above procedure, (*i.e.* a high eigenvalue) were processed further. Original samples were once again cut, but now, perpendicular to bedding. This procedure removes the 180° uncertainty between the two values derived from the "plane-of-bedding" peels. This is accomplished by determining the direction of grain imbrication (grains preferentially dip upstream) and thus ascertaining the true orientation of the grain. A repeat of the above procedure was performed, except instead of a "north-arrow", a reference "horizontal-line" (equivalent to the trace of the original bedding plane) was marked onto the slab and subsequently the peel.

Amalgamating information from both peel preparations, an accurate three dimensional orientation of the coarse clasts can be ascertained. This information is useful for the interpretation of paleocurrent direction and paleohydraulic conditions depositing these beds.

Method for acetate peel preparation.

Solutions:

Ethching Solution: 50:50 portion of 18% HF with distilled water. Staining Solution: 2 grams methylene blue to 1 litre distilled water.

Procedure:

Within a well ventilated fume hood, pour a small amount of HF solution into a plastic dish (enough to submerge the entire polished slab-face). Let the HF solution etch the face for 7 minutes. Remove, rinse well with distilled water and then let sit to dry. Cover the bottom of a dish with the methylene blue solution and place the dried, etched surface "face-down" for 10-15 minutes. Remove, rinse initially with tap water, then with distilled water. Let sit to dry.

To make the peel cover the etched, stained surface with acetone. Take a piece of pre-sized acetate and roll onto the face of the slab (rolling prevents the entrapment of air bubbles), let sit to dry. Remove peel.

Hints for peel preparation

(1) Be absolutely sure that all exposed skin and clothing is covered with plastic (gloves, apron, facemask, etc.).

(2) Properly dispose of all HF solutions (including rinse-water exposed to freshly etched

slabs)

(3) Thoroughly wash out fume hood before and after use.

(4) Peels can be made from various types of sedimentary rocks, but particular grades of acetate are better for specific cases. For sandstones and fine-pebble conglomerate 3-4 ml. acetate has found to be the best. Thicker acetate does not "pick-up" the peel, and thinner acetate rips too easily.

(5) Cut acetate so that the peel overhangs the entire slab surface.

(6) When removing the peel, peel back the acetate evenly around the entire ethched surface first. This way a "feeling" for the easiest direction for removal can be ascertained.

(7) After peels are removed store them in a book pressed between two pieces of tissue paper until needed for photographic enlargement.

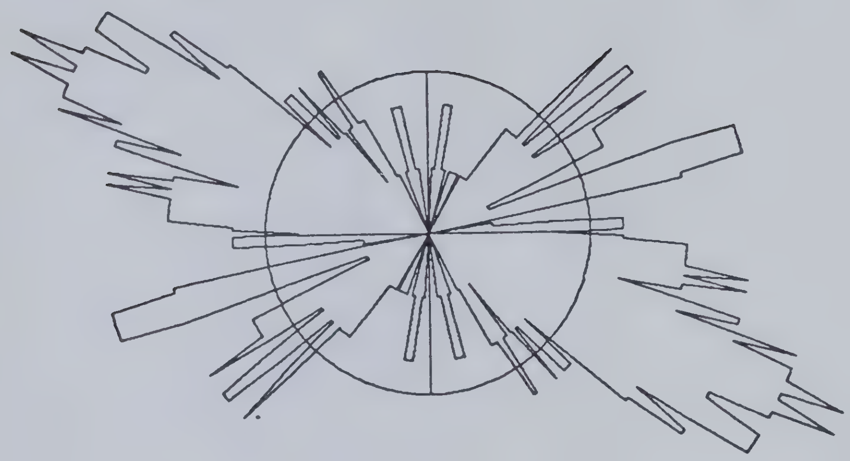
<u>(ii) Acetate Peel Plots; Figures: 5.1(a) through 5.1(m)</u>

Each peel plot represents 100 long-axis measurements.

Moving averages rose diagram interval is 5°.

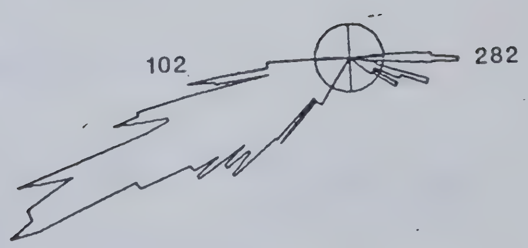
(a) PEEL 9

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
102.6	0.0	34.4124	0.6882

IMBRICATION

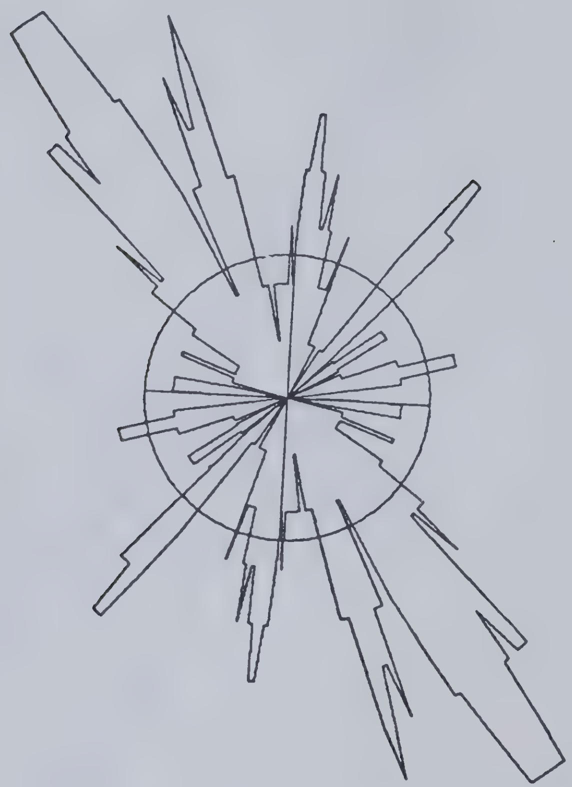


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
17.8	0.0	44.6281	0.8926

(b)

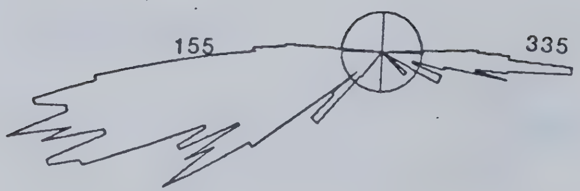
PEEL 15

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
335.4	0.0	33.0656	0.6613

IMBRICATION

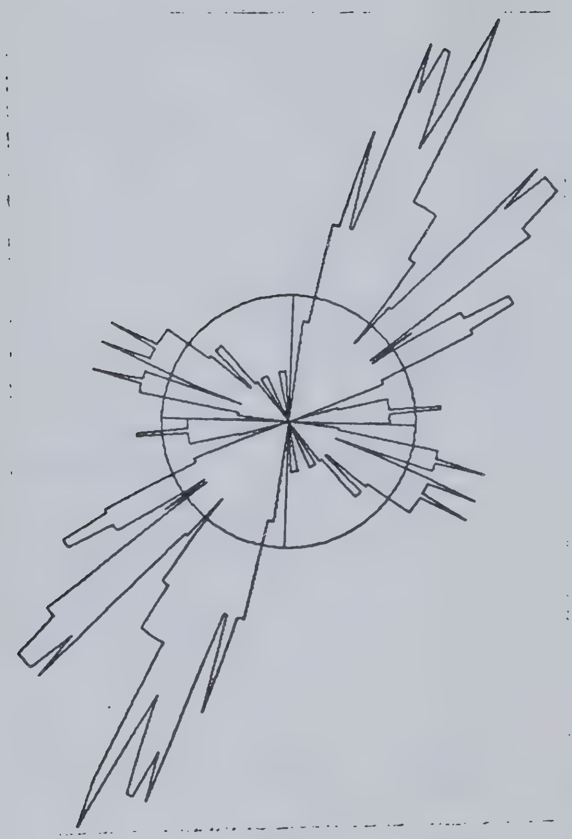


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
12.9	0.0	45.2855	0.9057

(c)

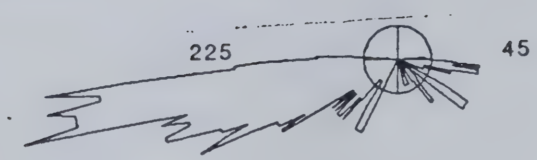
PEEL 17

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
45.7	0.0	33.3770	0.6675

IMBRICATION

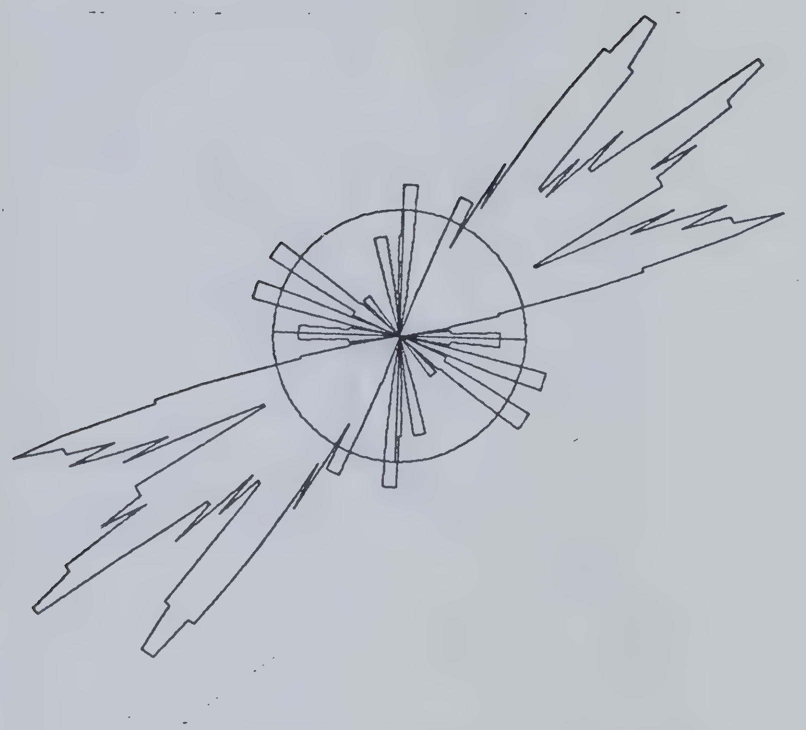


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
12.7	0.0	41.4083	0.8282

(d)

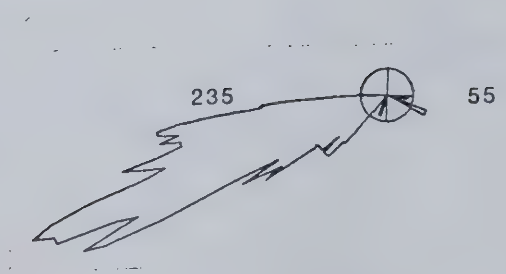
PEEL 30

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
55.1	0.0	36.7677	0.7354

IMBRICATION



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
21.9	0.0	46.5556	0.9311

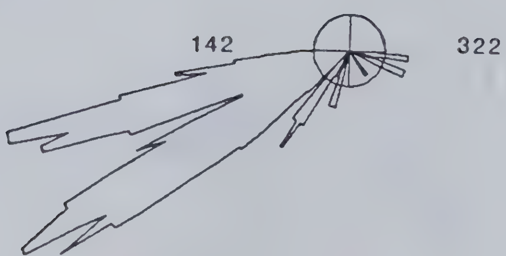
(e)

PEEL 33

PLANE-OF-BEDDING

TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
322.1	0.0	41.2855	0.8257

IMBRICATION

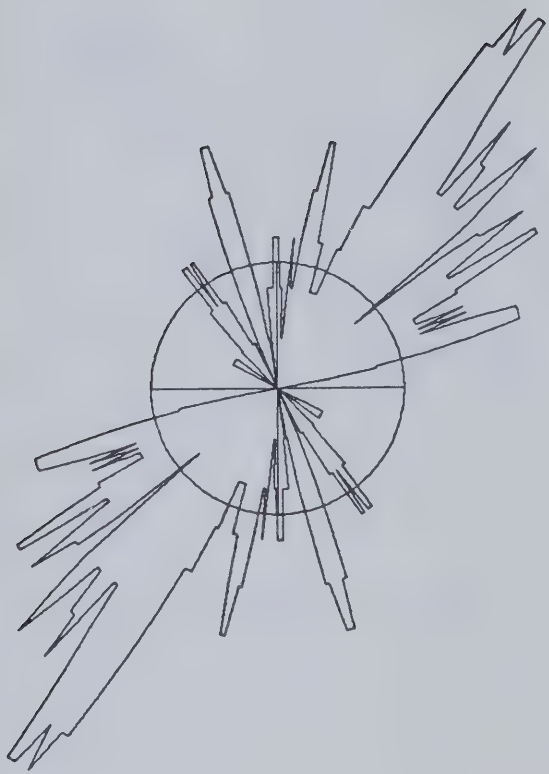


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
25.0	0.0	43.7906	0.8758

(f)

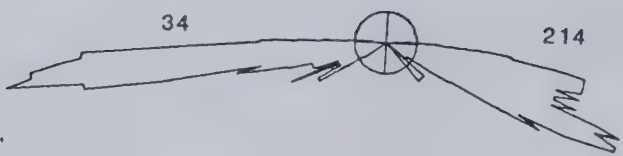
PEEL 37

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
33.9	0.0	37.1288	0.7426

IMBRICATION

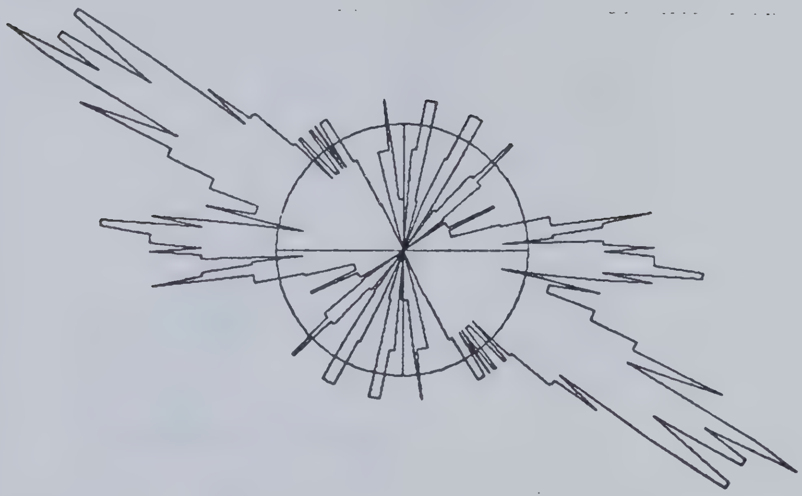


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
4.1	0.0	45.4801	0.9096

(g)

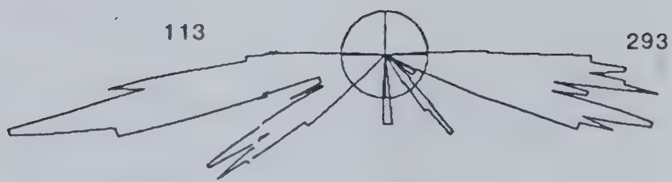
PEEL 43

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
113.1	0.0	34.3290	0.6866

IMBRICATION

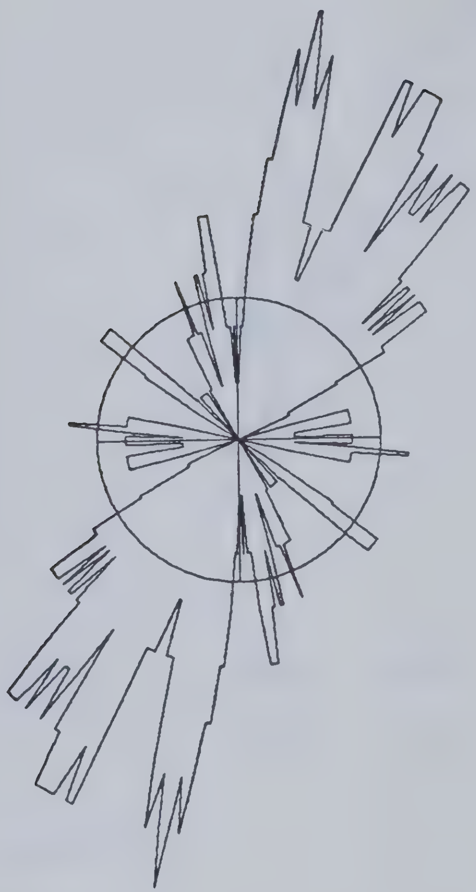


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
1.8	0.0	41.6533	0.8331

(h)

PEEL 45

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
26.2	0.0	35.9342	0.7187

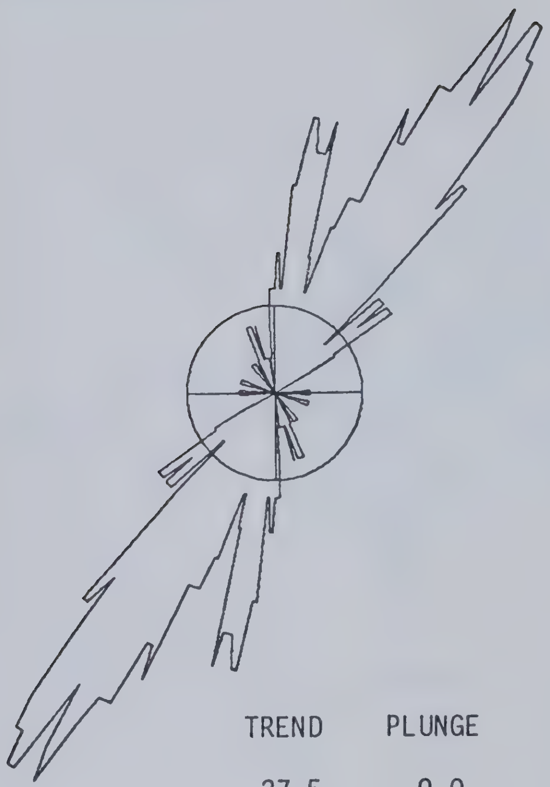
IMBRICATION

TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
13.6	0.0	44.8454	0.8969

(i)

PEEL 46

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
27.5	0.0	42.9159	0.8583

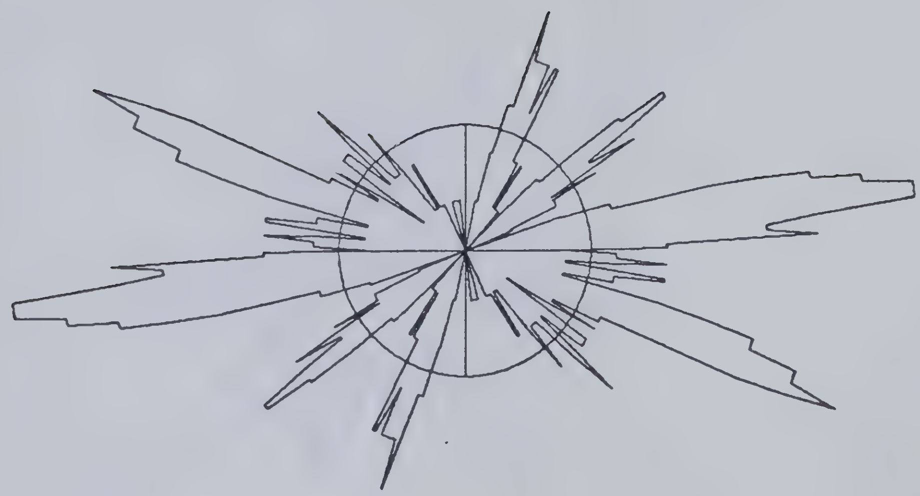
IMBRICATION

TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
56.7	0.0	42.4578	0.8492

(j)

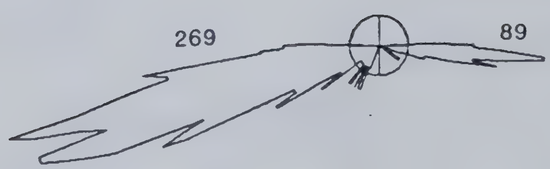
PEEL 47

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
89.2	0.0	34.6076	0.6922

IMBRICATION

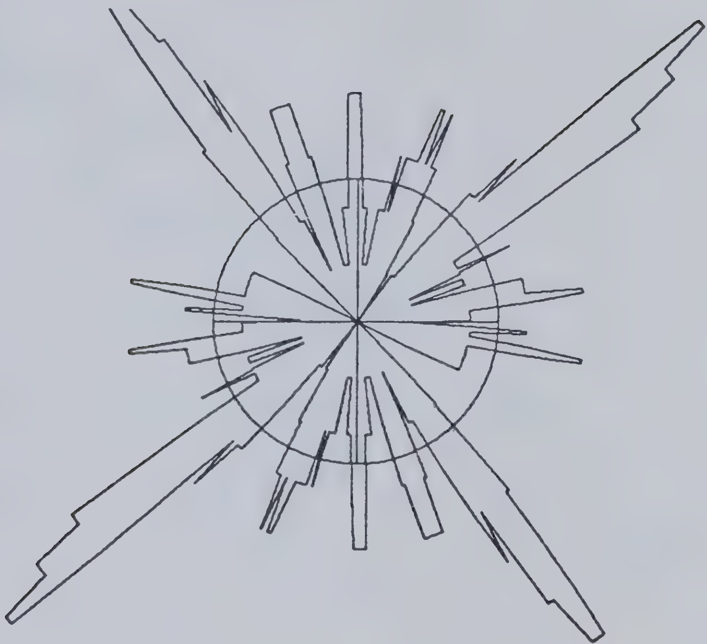


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
13.3	0.0	45.3038	0.9061

(k)

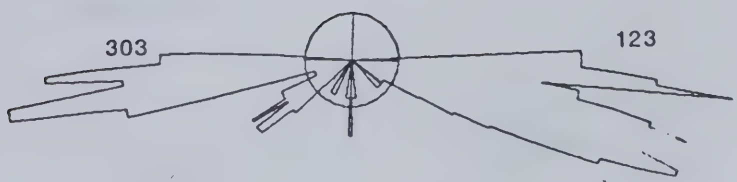
PEEL 50

PLANE-OF-BEDDING

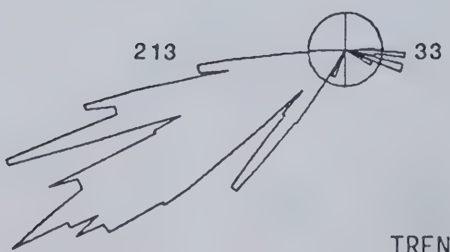


TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
33.3	0.0	27.3472	0.5469

IMBRICATION



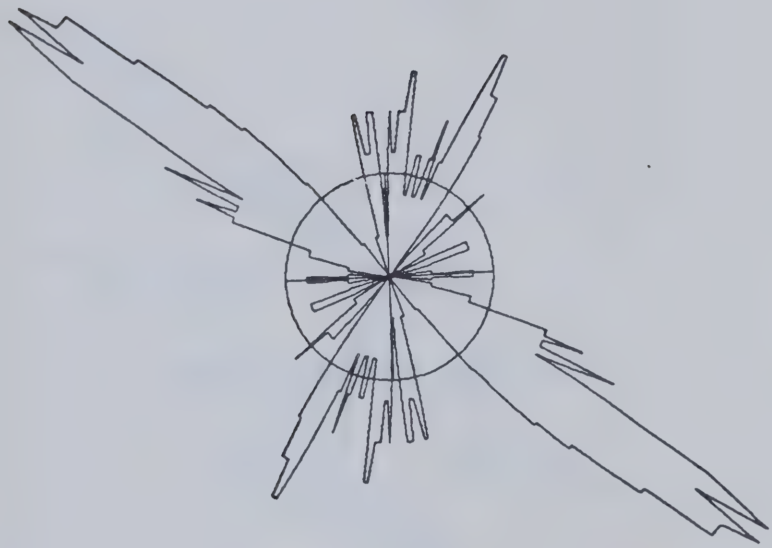
TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
1.7	0.0	42.9551	0.8591



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
24.6	0.0	44.9985	0.9000

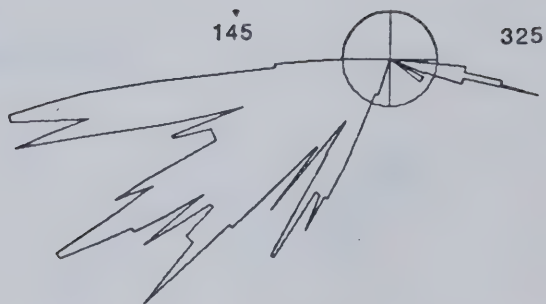
(I) PEEL 51

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
325.5	0.0	30.4782	0.6096

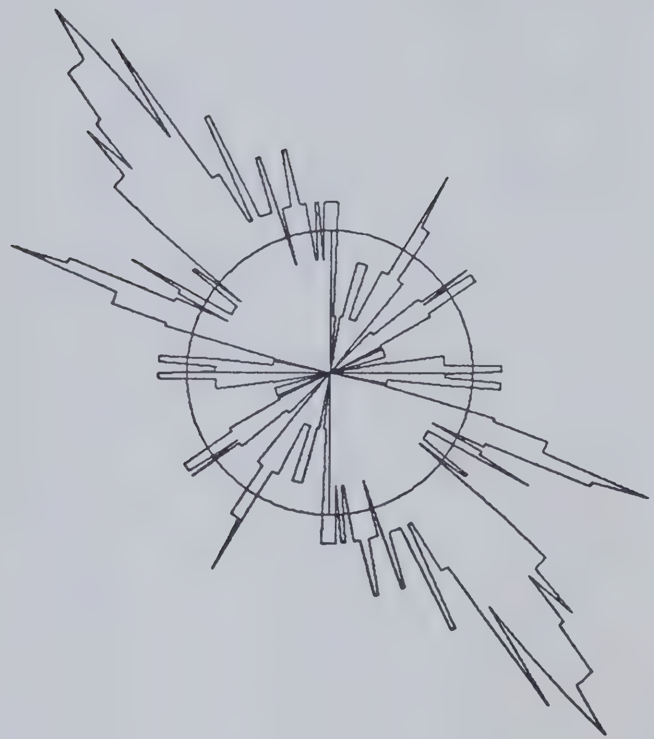
IMBRICATION



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
27.0	0.0	43.3374	0.8667

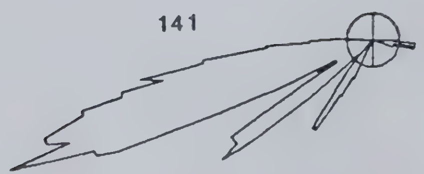
(m) PEEL 53

PLANE-OF-BEDDING



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
321.9	0.0	33.1093	0.6622

IMBRICATION



TREND	PLUNGE	EIGENVALUE	EIGENVALUE/N
20.9	0.0	46.1015	0.9220

(iii) Table 3: Summary of Acetate Peel Data

TABLE 3

SUMMARY TABLE FOR ACETATE PEEL DATA

PEEL NO.	PEEL LOCATION	FACIES OF BED	ORIENTATION OF LONG-AXIS	IMBRICATION OF LONG-AXIS	PALEOCURRENT DIRECTION
9	RMW SEC. 3 BED 51	12	102 282		282
15	RMW SEC. 5 BED 93	3	155 335		335
17	RMW SEC. 5 BED 109	6	45 225		45
30	RMW SEC. 7 BED 164	2	55 235		45
33	RMW SEC. 7 BED 194	3	142 322		322
45	RWS SEC. 8 BED 22	5	26 206		26
46	RMS SEC. 8 BED 22	7	28 208		28
47	RMS SEC. 8 BED 23	2	89 269		269
50	RMS SEC. 8 BED 66	5	123 303	no imbrication	33
50	RMS SEC. 8 BED 66	5	33 213		33
51	RMS SEC. 8 BED 76	2	145 325		325
43	RMS SEC. 9 BED 81	3	113 293	no imbrication	23
53	RMS SEC. 9 BED 86	4	141 321		321
37	RMS SEC. 11 BED 169	4	34 214	no imbrication	304

* RMW = REDOUBT MOUNTAIN WEST-FACE
* RMS = REDOUBT MOUNTAIN SOUTH-FACE

VIII. APPENDIX III

A. CROSS-BED PALEOCURRENT DATA

(i) Table 4: Cross-Bed Paleocurrent Data: Bath Creek Quarry

(ii) Table 5: Cross-Bed Paleocurrent Data: Redoubt Mountain

(i) Table 4: Cross-Bed Paleocurrent Data: Bath Creek Quarry

TABLE 4

BATH CREEK QUARRY
CROSS-BED PALEOCURRENT DATA

SECTION NO.	BED NO.	BED FACIES	ROTATED ORIENTATION
4	19	7	106/16 NE
			85/23 N
			88/22 N
			88/24 N
15	83	9	19/18 SE
			19/16 SE
15	85	9	18/20 SE
			39/24 SE
			38/22 SE
			46/17 SE
			26/22 SE
			22/15 SE
			10/19 SE
			52/26 SE
16	89	11	46/20 SE
			42/12 SE
			86/19 SE
21	121A	10	57/16 NW
			35/20 NW
25(B)	164	7	32/8 SE
			57/13 SE
			65/14 SE
			57/9 SE
26	169	10	10 190 *
27	171	10	90/30 S
29	179	7	44/11 SE
			36/12 SE
			64/10 SE
			28/10 SE
29	180	7	91/9 S

* trend of ripple train

(ii) Table 5: Cross-Bed Paleocurrent Data: Redoubt Mountain

TABLE 5

REDOUBT MOUNTAIN

CROSS-BED PALEOCURRENT DATA

SECTION NO.	BED NO.	FACIES OF BED	ROTATED ORIENTATION
3	42	10	164/26 NE
			168/31 NE
			138/25 NE
			112/21 NE
			90/19 N
			115/25 NE
			130/20 NE
4	54	7	108/10 NE
5	85	7	168/15 NE
5	102	10	115/3 NE
5	103	7	111/6 NE
5	104	10	72/5 NE
5	106	9	170/10 E
7	163	10	60/11 NW
			68/22 NW
7	184	7	09/6 W
			63/13 NW
7	194	7	159/20 SW
			147/16 SW
			217/14 NW
			198/20 NW
8	2	7	191/22 W
8	14		50 232 *
			38 218 *
8	30	7	215/17 NW
8	65	7	207/19 NW
			195/13 NW

TABLE 5 (cont.)

REDOUBT MOUNTAIN
CROSS-BED PALEOCURRENT DATA (cont.)

SECTION NO.	BED NO.	FACIES OF BED	ROTATED ORIENTATION
8	75	7	199/47 NW
			249/19 NW
			228/29 NW
			268/23 NW
			170/12 W
			238/23 NW
			07 187 *
			178 358 *
9	84	7	172/21 W
			148/16 NE
			250/18 NW
			200/22 NW
			170/17 W
			212/17 NW
			168/11 SW
9	107	7	162/23 SW
9	108	7	158/25 SW
9	116	7	163/20 SW
			207/8 W
9	123	7	126/15 SW
			164/32 W
			253/17 NW
			175/24 W
			162/29 W
			174/26 W
10	159	7	162/47 SW
			123/38 SW
			115/31 SW
			134/40 SW

trend of flute and other linear scour marks beneath Facies 7 beds

IX. APPENDIX IV

A. PETROGRAPHY

(i) Discussion of the Petrography of the Hector Formation at the Bath Creek Quarry and Redoubt Mountain

Discussion of the Petrography of the Hector Formation at the Bath Creek Quarry and Redoubt Mountain

Rocks were randomly selected at both study locations and prepared for thin section analysis. In all 31 thin sections, 20 from the Bath Creek Quarry and 11 from Redoubt Mountain, were analyzed and visual estimates of the bulk mineral compositions tabulated (Table 6 and 7).

Quartz is consistently the most abundant mineral in all studied thin sections. Quartz occurs on two scales: large crystals which actually represent individual sand grains, and cryptocrystalline quartz which is one of the major components of the fine-grained matrix. Carbonate minerals (predominately dolomite with minor calcite) are only observed at the Bath Creek Quarry area, but unfortunately are diagenetic rather than detrital in origin. In all the studied thin sections feldspars are dominately plagioclase (andesine in composition) with lesser potassium feldspar (microcline). All feldspars regardless of type, are usually heavily altered to white mica and a fine-grained matrix. Detrital micas are proportionally minor and are dominately muscovite with only minor biotite. Secondary euhedral hematite crystals and hematite staining are common in most thin sections.

The mineralogy of the studied thin sections is consistent at both study locations and is independant of stratigraphic height. This may suggest that sedimentation of the Hector Formation was not influenced by any extreme tectonic event, such as a volcanic eruption.

Bulk mineral composition of thin sections prepared from unaltered rocks at Redoubt Mountain and unaltered or only slightly altered rocks (those with minimal carbonate) at Bath Creek Quarry, indicate that the coarse clastic sedimentary rocks of the Hector Formation lie within the litharenite petrographic class of McBride (1963)(Figures, 52 and 53). Mineral assemblages characterizing these rocks are very similar to those reported from Precambrian basement rocks of the Western Canadian craton by Burwash and Krupicka (1970). By analogy, sedimentary rocks of the Uppermost Precambrian Hector Formation in the Lake Louise area are believed to have been derived from weathered Precambrian basement rocks of the primordial Canadian Shield.

TABLE 6

BATH CREEK QUARRY

SECTION NO.	23	24	1	4	4	4	4	5	5	5
BED NO.	146	150	2	18	19	20	21	24	27	28
QUARTZ	50-60	40-50	25-30	25	30	40-50	40	50-60	30	20
MATRIX	5	10-15	35-40	25	20	15	10-15	20-25	15	50-60
FELDSPAR	2-3	<1	trace	15	15-20	15	10-20	1-3	20	5
MICA	<1	1	3-5	5	5	5	3-5	1-3	3-5	3-5
CARBONATE	20-30	30-35	15-20	20	3-5	10-15	10-15	5-8	3-5	-
HEMATITE	-	1-2	-	-	5	1-3	3	10	30	5-10
ROCK FRAG.	1-2	-	1	2-3	-	<1	-	1	-	2-3
BLACK OPAQUES	1-2	-	5	1-3	-	3-5	-	-	-	-
SHPENE	-	-	1	trace	-	trace	trace	trace	-	trace
ZIRCON	-	-	<1	trace	-	trace	-	-	trace	-

TABLE 6 (cont.)

BATH CREEK QUARRY (cont.)

SECTION NO.	5	5	9	10	11	11	11	11	11	12
BED NO.	28	29	46	51	54	55	58	61	64	67
QUARTZ	40-50	40-45	25-30	40	55	25	60-70	60	65	65-70
MATRIX	15-20	10	50	10-15	5	50	20-25	10	10	15-20
FELDSPAR	20	5	3	5	10	10	3-5	3-5	2-3	3-4
MICA	1-3	3-5	10	3	-	2	<1	3-5	3-5	2-3
CARBONATE	10-15	3	-	20-25	5	-	-	-	-	-
HEMATITE	-	20-25	-	3	-	3	-	10	15	5-10
ROCK FRAG.	-	3-5	-	1	-	-	-	1-2	-	-
BLACK OPAQUES	<1	-	5	1-3	1-2	-	<1	-	-	-
SHPENE	trace	-	2	-	-	1	-	-	-	trace
ZIRCON	-	-	-	-	trace	trace	-	-	-	trace

* values represent percentages of visual estimates

- mica is predominatey muscovite with lesser biotite
- feldspars are commonly plagioclase (andesine), but microcline was often observed (where observed usually >1%)
- carbonates dominately dolomite with lesser calcite

TABLE 7

REDOUBT MOUNTAIN

SECTION NO.	1	1	2	2	3	4	5	5	5	5	8
BED NO.	9	15	26	32	39	58	94	101	140	156	76
QUARTZ	65-70	40-50	70-80	55-65	50-60	65-80	30-35	45-50	45-55	60-65	50-60
MATRIX	10-15	20-25	10-15	25-30	20-25	15-20	45-55	40-45	20-25	15-20	30-35
FELDSPAR	5-10	10-15	3-5	3-4	11	3-4	4-7	3-5	8-12	5-8	<1
MICA	1-2	5-10	1-2	1	10-15	1-2	1-2	3-5	1-2	2-3	3-10
CARBONATE	-	-	-	trace	-	-	-	-	trace	-	-
HEMATITE	3-5	5-10	1-2	-	-	3-5	-	-	5-10	-	-
ROCK FRAG.	<1	-	2-3	-	<1	-	1	-	1-2	-	-
BLACK OPAQUES	-	-	-	-	1	1	-	-	-	-	-
SHPENE	-	1-2	-	-	<1	-	-	-	-	<1	<1
ZIRCON	-	-	-	-	trace	-	-	-	-	-	<1

* values represent percentages of visual estimates

- mica predominately muscovite with minor biotite
- feldspars: slightly greater abundance of plagioclase (andesine) than orthoclase (microcline)

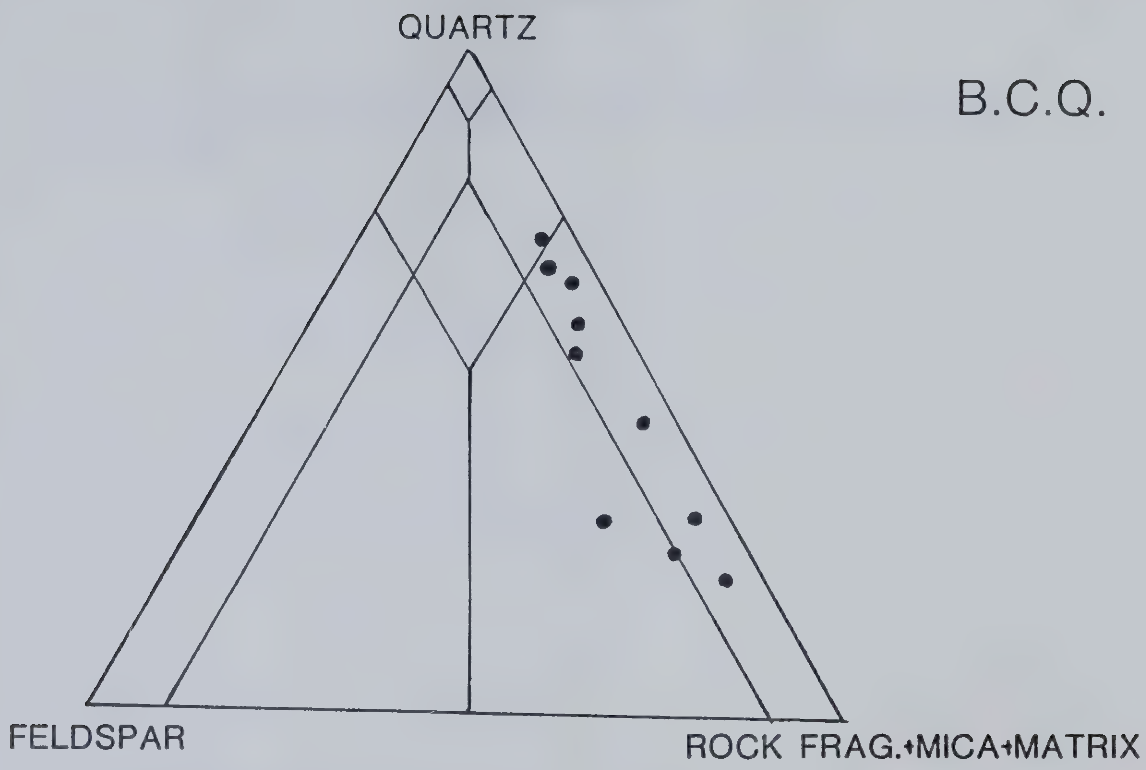


FIGURE 52: Classification of Coarse Sandstones at Bath Creek Quarry.

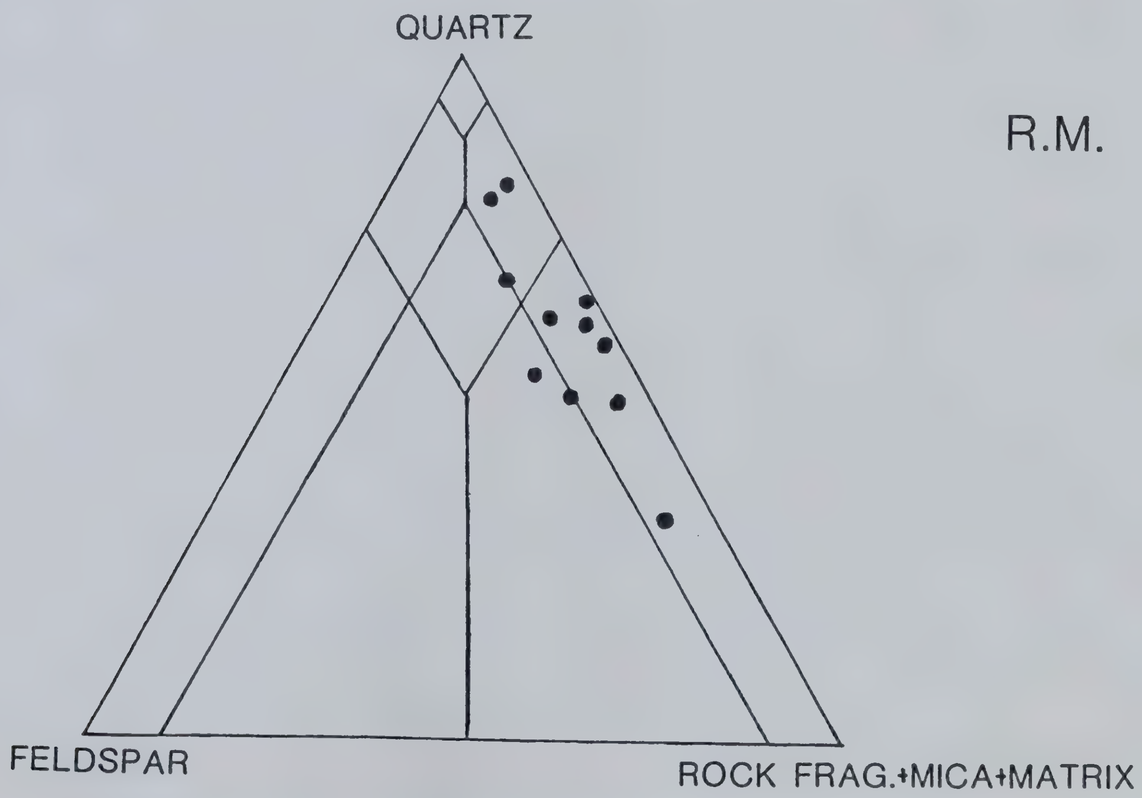


FIGURE 53: Classification of Coarse Sandstones at Redoubt Mountain.

X. APPENDIX V

A. METHOD FOR CALCULATING AVERAGE FLOW VELOCITY FOR BEDFORM DEVELOPMENT

Method for Calculating Average Flow Velocity for Bedform Development

1) For fully turbulent flow: Re) 1000 and the Shields B=0.06

substituting into the equation:

$$U_{*c} = \frac{0.06g\ (p_s - p_f)ds}{p_f}$$

where U_{*c} = critical shear stress

$g = 9.8$ m/s/s
p_s = density of the sand grains
p_f = density of the ambient fluid

ds= grain size

U_{*c} is the velocity at which grains of size (ds) are able to move.

2) To calculate average flow velocity use:

$$\frac{\bar{U}}{U_*} = \frac{8}{f_0 + f_i}$$

where $\bar{U}$ = average velocity
U_* = average shear velocity
f_0 = frictional factors due to bottom roughness
f_i = frictional factors due to interfacial shrear stress

Assuming negligible f_i (interfacial shear stress); therefore $f_i = 0$.

$$\frac{\bar{U}}{U_*} = \frac{8}{f_0}$$

Values for f_0 are given in Simons et al., 1965 and Hein, 1982a.

U_* can be read directly off Figure 7- 21A in Middleton and Southard (1977).
U_* differs from U_{*c} since it is dependant upon bedform type.

If $\bar{U}$ is calculated by Shields Criterion (i.e. U_{*c} is substituted for U_*), then $\bar{U}$ represents the average minimum flow velocity.

If U is calculated using U_* , $\bar{U}$ represents the average flow velocity.

XI. APPENDIX VI

A. MEASURED SECTIONS AND CHANNEL-FILLING EVENTS: REDOUBT MOUNTAIN (FOLD-OUT)

B. MEASURED SECTIONS AT BATH CREEK QUARRY (FOLD-OUT)

Numbers on the left-hand side of the sections refer to the measured bed number. Numbers on the right-hand side of the sections refer to the sedimentary facies of that bed (refer to text for descriptions of the individual facies).